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SOME POST-PLIOCENE BURIED SOILS OF CENTRAL UNITED STATES

JAMES THORP, W. M. JOHNSON, AND E. C. REED

WITH 2 PLATES

Introduction

PRACTICALLY all Pleistocene geologists and soil scientists have noted the wide occurrence of buried soils at several stratigraphic positions, some strongly developed, and some with profiles that could have developed in a few hundred years. Many buried soils were partly eroded before burial, and some of their horizons are missing or truncated from place to place. In some, only the leached and weathered parent material remains as evidence of a long period of soil formation.

This paper touches on buried soils in central United States from the southern border of the Mankato (last glacial) drift to the Gulf of Mexico, and from the Appalachian Mountains west to the Rocky Mountains. Emphasis is on the buried soils of Nebraska, Iowa, Illinois, Missouri, and Kansas where considerable work has been done in recent years. Co-author Johnson is collecting profile descriptions and is analysing samples of the buried soils in order better to estimate the conditions under which they developed. His findings will be collected later in a thesis connected with his graduate studies at the University of Nebraska.

Although buried soils have long been known in central United States, and much has been written about them, we find little published information on the details of profile characteristics. The strongly developed buried soils in the glaciated and periglacial areas were formed primarily during interglacial stages of the Pleistocene. Weakly developed buried soils, especially notable in the late Pleistocene loess, may or may not be related to fluctuations of the Wisconsin ice front. A brief review of selected references outlines previous work and suggests the need for more detailed studies.

Previous Work

Fossil soils were first recognized and described probably in the late 1800's, at about the same time that the study of soils began to develop into a true scientific discipline. Glinka and Krasnov (cited by Polynov, 1927) studied so-called 'two-stage' soils in the Transcaucasian region and concluded that the underlying red-coloured materials are the products of ancient weathering of a lateritic or red-soil type. The present climatic and biological environment of that region favours the podzolization process. Glinka hypothesized a sub-tropical environment in Tertiary (actually, probably early Pleistocene) time that produced a red soil high in sesquioxides and a change from that environment to the present one during and following the Pleistocene.

According to Polynov (1927), the first observations of true buried or

fossil soils were those of Feofilaktov in the loesses of the Lubny district, Poltava Government. Similar buried soils were noted in Ukrainia in the region of the Don River, in other parts of Russia, and in Poland. Krokos (1926, 1927) made detailed studies of the loesses and fossil soils of Ukrainia. On the basis of stratigraphic and pedologic evidence he correlates three fossil soils with interglacials following the retreat of Günz, Mindel, and Riss glaciers, respectively, and postulates that the two older interglacial stages represent times of more humid climate than the latest interglacial or the present climate.

The earliest observations of fossil soils in North America were made by geologists. Only in comparatively recent years have North American soil scientists become interested in the study of buried profiles. Worthen (1866) was perhaps the first to recognize that a definite soil 'horizon' separates the Illinois till from the overlying loess. Later Leverett (1898 *c*) suggested the name Sangamon for this weathered (soil) zone. Leverett (1898 *b* and *c*) also proposed names for two other weathered zones or fossil soils, Yarmouth for the one between the Kansas and Illinois tills, and Peoria for one between the Iowa loess and the Shelbyville till. In time the interpretation of these names changed so that some authors now use the name Sangamon for the loess that was deposited during the retreat of the Illinois glacier, Yarmouth for the late-glacial alluvium and loess that overlap the Kansan till, and Peoria for the loess deposited following Iowan glaciation, exclusive of the late-Wisconsin (Condra *et al.*, 1947).

A complete review of the literature relating to North American buried soils is not presented here. Most of the work on these ancient soils has been done by geologists, and most of it has been directed towards one or both of two aims: to establishment of a stratigraphic datum (W. Bryan, 1939; Condra *et al.*, 1947; Frye 1949; Frye *et al.*, 1949; Kay, 1939; Kay *et al.*, 1928, 1943, 1920; Movius, 1949; Peltier, 1949; Schultz and Stout, 1948), and to interpretation of the climatic and physiographic history of an area (K. Bryan, 1948; Bryan and Albritton, 1943; Leighton and MacClintock, 1930; Lugn, 1935; Schultz and Stout, 1945; Simonson, 1941). The first studies, of which the works of Leverett, Kay, and Leighton provide classic examples, were all within the region of continental glaciation. In the past two decades the observation and study of fossil soils has been extended, first to periglacial deposits and finally to regions entirely without direct influence of glaciation.

The Afton, Yarmouth, Sangamon, and Brady soils are all prominently developed in the State of Kansas, but the Afton soil is exposed in few places. Frye and his co-workers (1949) have made extensive studies of these soils, using stratigraphic, petrographic, and paleontologic techniques. They have shown that the Sangamon soil serves as a regional stratigraphic datum and furnishes a record of Sangamonian climate over western, central, and north-eastern Kansas. Particularly noteworthy is the fact that contrasts in Sangamon soil character from north-west to south-west exceed contrasts in modern soil profiles, suggesting that there has been a significant change in climate in south-western Kansas since Sangamonian time. The work of A. B. Leonard (1950) on Pleisto-

cene molluscs supports the pedologic evidence of gradual 'drying-up' of the Great Plains region since Yarmouthian time.

Bryan and Albritton (1943) suggested a technique for using fossil soils and 'complex' (two-stage) soils to interpret past climatic changes. They point out that the most useful paleopedological evidence is likely to be preserved in deposits along the boundaries between humid and semi-arid climatic belts, because here relatively small changes in climate are likely to produce striking changes in the soil morphology. They applied this technique to the study of colluvial deposits in the Trans-Pecos area of Texas, and K. Bryan (1948) used it to determine the relative ages of some small volcanoes in the southern part of the Valley of Mexico.

No attempt is made here to enumerate all the places in the world where buried soils have been reported. It is safe to say that fossil soils of determinable age exist everywhere in the world where cataclysmic changes in climate or in rate of deposition of sediments, alluvial and eolian, were associated with glaciation, tectonic movements, &c. Mohr (1944) reports fossil red earths in Java. Movius (1949) used buried soils on stream terraces as aids to correlation of the ages of Pleistocene terraces in Java, India, and China. Pendleton *et al.* (1932, 1935) reported fossil soils in the loess deposits of Suiyuan Province and near Harbin, China. Thorp (1935, 1936) gives descriptions of several buried soils in the loesses of north-western China, and reports analyses of some profiles. These Chinese fossil soils are valuable stratigraphic markers there as they are in other parts of the world. Thorp saw many examples of buried soils in the volcanic-ash deposits of Japan and the Philippine Islands.

Johnson found buried soils common in the regions of volcanic-ash deposits and in the terrace deposits of larger streams of Colombia, South America. W. Bryan (1939) suggested that the 'Red Earth Residuals' of Queensland may be used as a stratigraphic datum and as a basis for correlation of some of the land surfaces in Queensland with those in other countries. Fossil soils have been reported and described in Europe (Joffe, 1936) and in Africa.

Buried Soils and the Pleistocene Section in Central United States

Fig. 1, outlining the Pleistocene section in central United States, is a recent modification of the original correlation table of Condra *et al.* (1947, Fig. 6). It shows the four major glaciations—(1) the Nebraskan, (2) the Kansan, (3) the Illinoian, and (4) the Wisconsin—and the major periglacial deposits of the Great Plains. Although each of the four glaciations may have been complex, only the last major glaciation, the Wisconsin, is exposed widely enough and preserved well enough that evidences of minor advances and retreats of the ice can be easily recognized. Sub-stages of the Wisconsin glaciation generally recognized in the United States are, from older to younger, the Iowa, the Tazewell, the Cary, and the Mankato. It is now thought that the Iowa–Tazewell and the Cary–Mankato formed two nearly synchronous pairs, with a significant time interval between the pairs (Fig. 1).

The theoretical succession of events is as follows, beginning with the earliest glaciation and continuing to the present:

1. *The Nebraskan–Aftonian.*—The Nebraska ice sheet advanced as far south as Missouri and north-eastern Kansas and nearly as far west as the Big Blue River in Nebraska. Some gravelly and sandy outwash from the main ice front, and doubtless from the Rocky Mountain glaciers, accumulated during both the advance and retreat of the Nebraska ice

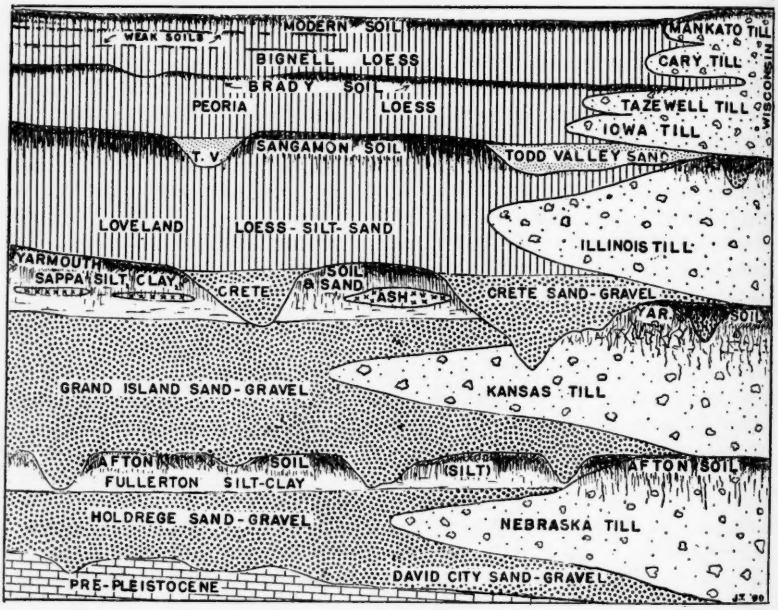

FIG. 1. Generalized Pleistocene section of central United States, showing the succession of glacial deposits of north-central States and periglacial deposits as they occur in Nebraska, Kansas, and adjacent areas. Our present interpretation of the relationships of buried soils to Pleistocene deposits is shown.

sheet. The outer edge of the till is interbedded here and there with water-laid sand, gravel, and silt, suggesting fluctuation in the ice front. During the retreat of Nebraska ice, outwash streams carried much silty material which remains partly a stratified and partly an unstratified, probably eolian, deposit. While the name 'Aftonian' has been applied by some workers to the silty late-Nebraskan outwash, it seems more appropriate to reserve the name Afton* for the Nebraskan–Kansan interglacial stage, as did Leverett (1898 *a*).

The melting of Nebraska ice was followed by a very long ice-free

* Throughout this paper place-names are used for formations or deposits and buried soils, and adjective endings are added to these names to apply to time concepts. E.g. 'Afton soil', 'Aftonian time'.

period of soil formation, the Aftonian Interglacial, during which the calcareous drift was leached to considerable depths, and soils of various kinds were formed. Much of the buried soil, formed during the Aftonian Interglacial, is dark grey, carbonaceous, and clayey in the upper part, and medium grey, tough, plastic, and very clayey in the lower part. The material, as a whole, has been called 'Nebraskan gumbotil' following the introduction of this name by Kay (1916). The word 'gumbo', originally an African word for the mucilaginous pods of the okra plant, is a common name among American farmers for any sticky clayey soil that is hard to plough.

Only part of the 'gumbo soil' is developed from glacial till. Much of it was formed entirely in silty alluvial, lacustrine, or eolian deposits. Some of it developed entirely from boulder-clay till; and in many places it is clear that the profile was formed partly in water- or wind-laid deposits and partly in strictly glacial deposits. The true gumbo soil with its grey and mottled gley subsoil, clayey texture, and blocky to massive structure seems to have formed under the influence of a permanent high water-table. Remains of peaty, water-loving plants in the uppermost foot or two confirm poor drainage during formation. Most of the gumbo soil occurs on remnants of an old land surface which, if reconstructed, would have very low relief.

Most of the Nebraska drift with its Aftonian soil was buried so deep beneath later deposits that it crops out only on the slopes of deep valleys, where it causes seepage and landslides during wet weather. Much of the information regarding it comes from a study of subsurface samples taken with drilling equipment used in ground-water exploration. The Conservation and Survey Division, University of Nebraska, and the Geological Survey of Kansas—both co-operating closely with the Ground-Water Division of the United States Geological Survey—are leading in this field of study. In Nebraska the gumbo soil is found on uneroded parts of the Nebraska till, on the late Nebraska silt which overlaps it, and on the Fullerton silt and clay of central Nebraska, outside the glaciated area (see Fig. 1).

Although the Aftonian interglacial time-interval is known to be represented by the gumbo soil and its catenary associates of several kinds, little is known regarding the age of some of the very old soils outside glaciated areas. Possibly a few of the red and yellow soils—especially the red ones—of southern United States may date back as far as the Aftonian.

2. *The Kansan–Yarmouthian.*—The Kansas ice sheet advanced over much of the territory covered by the Nebraska ice, but it extended considerably farther in Nebraska and Kansas, some miles beyond the Big Blue River and a short distance south of the Kansas River in several places. The sequence of events was much like that of the Nebraskan glaciation and deglaciation. Fig. 2 shows how the Kansas glacier picked up frozen blocks of Afton soil and incorporated them in the Kansas till.

Late during the Kansas deglaciation there was a tremendous volcanic eruption, or series of eruptions, possibly in north-central New Mexico

(Swineford, 1949). The ash (the Pearlette) from this eruption drifted as far east as central Texas, eastern Kansas and Nebraska, southern Minnesota, north-western Missouri, and north-western Iowa. Some of it accumulated in depressions where it was buried later by the silt, sand, gravel, and clay of the upper part of the Sappa formation (see Fig. 1). Since there was apparently only one important ash fall during middle Pleistocene time in central United States, geologists confidently use the Pearlette ash as a stratigraphic marker for late Kansan (Sappan) time.

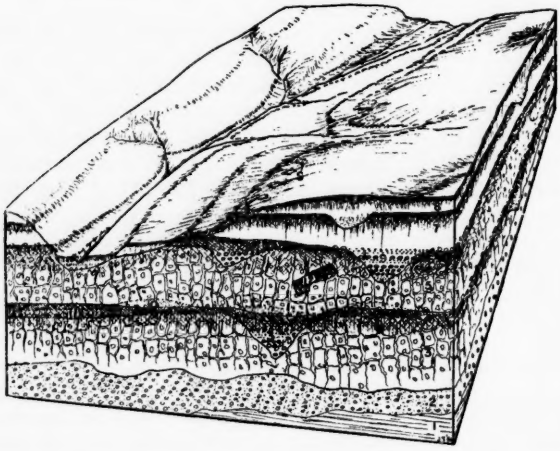

FIG. 2. Block diagram showing succession of Pleistocene deposits and buried soils typical of western Iowa, north-western Missouri, north-eastern Kansas, and south-eastern Nebraska. In any given place, one or more of the deposits and the accompanying soils may be lacking; and some of the buried soils may be truncated. Note 'shoulders' or faint scarps where buried soils crop out. Solonetz (S) spots occur at some places near junctions of younger deposits with buried soils.

1. Paleozoic or Mesozoic bedrock. 2. David City (earliest Pleistocene) gravel and sand. 3. Nebraska glacial till and outwash (the first glaciation). 4. Afton soil (first interglacial). 5. Kansas glacial till (the second and maximum glaciation). 6. Yarmouth soil (second interglacial) from Kansas till, outwash, and Sappa sediments. 7. Loveland loess (Illinoian or third glacial age), and Sangamon soil (third interglacial). 8. Peorian and later loess (Wisconsin or fourth glacial age), and modern soil. 9. Crete (early Illinoian age) gravel and sand. 10. Pro-Kansan silt and sand. 11. 'Afton silt' (late Nebraskan age). 12. Block of Aftonian-aged soil in Kansas glacial till.

A long period of soil formation, the Yarmouthian Interglacial, followed the retreat of Kansas ice and the deposition of the Pearlette ash and other stratified materials of the Sappa formation (the 'Upland' of Lugn, 1935). This gave rise to the Yarmouth soils, part of which Kay and Apfel (1928, p. 130), called 'Kansan gumbotil', which they said was capped by a 'distinct soil zone' or 'forest bed'.

The Yarmouth soils formed at the surface of whatever land was exposed at the time. Some of this land was well drained and some of it was flat and poorly drained. 'Gumbo' soils developed on the smooth,

poorly drained areas, and 'normal' or 'zonal' soils with reddish B horizons formed on the well-drained areas. The well-drained catena members are hard to distinguish from soils formed during the Sangamonian Interglacial time. Parent materials included Kansas glacial till, Kansas loess, Kansas outwash of sandy, silty, and clayey textures, and various kinds of bedrock exposed in many parts of the country that were neither reached by glaciers nor covered by loess.

Much of the Yarmouth soil was truncated by erosion and the remnants were buried later by materials of Illinoian and Wisconsinian ages. Buried Yarmouth soils are more of gumbo types (in places with loamy A horizons) than of normal ones, doubtless because the flatter areas were the last to be attacked by erosion and the first to be covered by loess.

3. *The Illinoian–Sangamonian.*—Following the very long Yarmouthian Interglacial time, the Illinois ice sheet advanced over central United States, but failed to reach large areas in southern Iowa, northern Missouri, eastern Nebraska, and north-eastern Kansas (see Flint's glacial map of North America (National Research Council, 1945)). The westward extent of this ice sheet is not fully known, but in northern latitudes according to Alden (1932), it may have extended far out on the Great Plains in South Dakota, North Dakota, Montana, Saskatchewan, and Alberta. In any case, a great deal of Loveland loess and other materials were deposited in periglacial areas during both the advance and retreat of the Illinois ice (see Fig. 1). A vast area in Nebraska and Kansas, in eastern Colorado, and southward from Illinois to Louisiana, along the east side of the Mississippi River, was covered by loess, wind-blown sand, or by water-laid gravel and sand during this time. Geologists believe that outwash sediments and some loess were deposited contemporaneously in eastern United States (Peltier, 1949). No doubt much alluvium was deposited in southern States, contemporaneous with Illinoian glaciation.

The Sangamonian Interglacial, a very long period of soil formation, followed the retreat of Illinois ice. On the one hand, dark-coloured A horizons suggest that most of the buried Sangamon soils west of the Missouri River in Kansas and Nebraska, and probably farther west, were formed under grassy vegetation. On the other hand, deep leaching, light-coloured podzolized A horizons, and reddish-brown B horizons of many of the buried Sangamon soils in Iowa and Missouri and eastward suggest humid climates and forest cover in that region (Baker, 1924; Simonson, 1941).

During and immediately following the long Sangamonian Interglacial, erosion truncated some of the soils, but large areas remained intact.

4. *The Wisconsinian–Modern.*—The Wisconsin ice spread over an enormous area of North America and covered much, but not all, of the land that had been invaded by the three preceding ice sheets. Large areas of Illinois drift remained uncovered, notably in eastern Iowa and in southern Illinois, Indiana, and Ohio. Loess accumulated during both the advance and retreat of Wisconsin glaciers, especially during the Iowa and Tazewell sub-stages, and, to less extent, during the Cary substage. Little loess accumulated on the Mankato till, but much loess

outside the drift area has been assigned tentatively to the Mankato substage (Schultz and Stout, 1945).

The first Wisconsin loess seems to have collected very slowly on the old Sangamon soil in Nebraska and Kansas. Soil formation kept pace with deposition, and the decay of grass roots darkened the first layers of Wisconsin loess. Dark granular silty A horizons as much as 3 ft. thick, or even more, developed in some places before loess began to accumulate too rapidly for soil formation to keep pace. Vertebrate paleontologists call the over-thickened A horizon and the lower part of the overlying loess the 'Citellus zone', named from the small rodents whose skeletons are found preserved in great numbers in this and in lower horizons (Lugn, 1935). Ancient rodent burrows (crotovinas) extend from the upper, younger, part of the buried soil profile into the older lower A, B, and C horizons developed in Loveland loess, and even into the Sappa deposits.*

The thin upper loess of the Citellus zone (Schultz and Stout, 1945, 1948) of Nebraska, Kansas, and adjacent States may correlate with the Farmdale loess of southern Illinois, which the Pleistocene geologists of Illinois (Leighton and MacClintock, 1949) consider to be a pre-Iowan, post-Sangamonian loess.

The Peoria loess, named from Peoria, Illinois, is more recent than the Farmdale loess, and seems to be associated with the Iowa and Tazewell sub-stages of the Wisconsin glaciation.

The greatest and most extensive deposits of loess were made during Iowan and Tazewellian times, both close to the glacier fronts and in more distant areas, especially along the large glacier-fed and trans-plains rivers like the lower Mississippi, the Platte, the Missouri, and the Arkansas, and adjacent to the drier parts of the Great Plains east of the Rocky Mountains. Contemporaneously, a great amount of eolian sand was heaped up in various parts of the Great Plains. The largest dunes are in north-central and south-western Nebraska, where the total area is about 13 to 14 million acres; along the Arkansas River in the vicinity of Great Bend, Kansas; and along the various rivers that flow across the high plains in Oklahoma and Texas.

As far as we know, most of these sand-dunes were formed during the late Pleistocene, although some may be older. Dark-coloured sandy loam soils with reddish-brown sandy clay loam subsoils along the Kaw River, between Topeka and Lawrence, Kansas, are developed from sandy alluvium reworked by the wind at least as early as Illinoian time.† Soils buried within the sand-dunes indicate that dune formation alternates with periods of stability.

We find very few and very weakly developed buried soils within areas of Wisconsin glacial till; but some periglacial loess deposits in Nebraska and Kansas have successions of buried soils that are known to be of Wisconsin age. At least one fairly well-developed Chernozem-like soil

* Verbal information from Dr. C. B. Schultz, Director, University of Nebraska Museum, and field observation by the authors.

† Verbal opinion given by Dr. John Frye, Executive Director of the Geological Survey of Kansas.

appears in Nebraska and Kansas at the top of the loess correlated as Peoria (Iowa–Tazewell). Schultz, Stout, and others (Schultz and Stout, 1948) have given it the name 'Brady'. Some of it is a Chernozem-like silt loam without textural variation in the profile; and some of it has a mottled subsoil suggesting that it may be a preserved Wiesenboden or Humic-Gley soil. The Bignell loess, that overlies the Brady soil in places, has in it a succession of dark bands or weak soils that represent short periods of pause or slow-down in loess deposition. 'Double soils' with one dark A horizon superimposed over another, and in places with claypans in the buried soils as described by Williams (1945), are very common in the regions where Chernozem, Chestnut, and Brown soils are developed in Peoria and younger loess. The 'double soils' are most distinct near the probable sources of the loess, and the two A horizons blend on the plains a few miles from these theoretical sources. Thus the 'Brady soil' in many places is a part of the modern soil. Schultz and Stout (1948), Lueninghoener (1947), and a number of others are using loess-mantled river terraces as a means of correlating Pleistocene loess deposits and buried soils with various glacial deposits. Much still remains to be done in this field.

The study of radioactive carbon, developed by Libby and associates (1949), is a recent development that will be useful in making final correlations. It is expected that determinations of the proportion of radioactive Carbon-14 in peat beds, buried forests, buried soils, and in charcoal from loess-mantled camp-fire sites of ancient man may give us an exact chronology for deposits less than 30,000 years old.

Relationships of Buried Soils to Modern Land Forms and Present-day Soil Profiles

The Afton soils

Most of the Nebraska till is buried so deep beneath later deposits that the Aftonian interglacial soils crop out only along deep valley sides. Hence the Afton soil has only the most local effects on present-day soils, landscapes, and land forms in glaciated areas. Little has been done outside of areas of glacial and periglacial deposits to determine whether any soils of Aftonian age still remain there.

Kay and Apfel (1928) describe many sections that include their 'Aftonian soil', which appears to be the uppermost horizon of the Afton soil as we understand it. Following is an excerpt from their description made in a railroad cut 1½ miles west of Manning, Carroll County, Iowa. We have excluded the description of the overlying Kansas till and Perioa loess.

Soil band, Aftonian, containing carbonaceous material . . 4 inches thick
Gumbotil, Nebraskan, gray to drab-colored; few pebbles. The upper six feet is fine-grained, gray, and is less sticky and gumbotil-like than the lower seven feet, which is leached but has some calcareous concretions . . 13 feet thick
Till, Nebraskan, unleached, oxidized, light yellowish color on dry surface; mottled brownish with gray when damp; many calcareous concretions, especially in upper ten feet . . . . . 17 feet thick

Elsewhere the gumbotil is described as being very clayey, sticky, and plastic, and breaking to small polyhedral blocks when dry. We consider the second (the gumbotil) horizon to be typical gley. Recent field studies indicate that the upper few feet of 'gumbotil' may be developed from Loveland loess.*

In the deep valleys of southern Iowa landslides are frequent on outcrops of the Afton soil.

The Yarmouth soils

In parts of Nebraska, Kansas, and perhaps in Texas, some of the buried Yarmouth soils have become exposed and do affect land forms. Short and abrupt changes in slope gradient on hill-sides show where heavy B, or gley horizons, more resistant to erosion than friable materials above and below, have been exposed by dissection. The clayey material makes a low ridge or 'shoulder' wherever the old soil is exposed. Most of the Yarmouth soil, however, is either buried beneath later deposits or has been removed entirely by dissection. We do not yet know just which of the old relict but unburied soils of high interfluves and terraces of the southern States may be of Yarmouthian age. For example, a black claypan soil on the Prairie–Chernozem border south of Hutchinson, Kansas, may prove to be Yarmouthian.

Probably some of the old, strongly developed Red Podzolic soils of the southern States may date as far back as Yarmouthian and Kansan times. Certainly many Red Podzolic soils are either relict or, at least, polygenetic. For example, near Memphis, Tennessee, Loveland loess blankets a Red Podzolic soil, much like Ruston fine sandy loam, formed in older materials. This old soil has a light-coloured, leached, sandy loam A horizon of considerable thickness, underlain by a yellowish-red acid clay loam B horizon that grades below to mottled red and yellow acid sandy clay. While it seems likely that this buried soil was developed from materials that were originally calcareous, no calcium carbonate can be detected anywhere in the profile at the present time. Since this buried soil is mantled by Loveland loess, Yarmouthian or possibly greater age is indicated. South-eastward from Memphis, across the upland, the Illinois and Wisconsin loess-mantles become progressively thinner; and in north-eastern Mississippi and northern Alabama one finds Red Podzolic soils at the present surface very much like the one buried near Memphis. Thus physiographic evidence suggests that some of the Red Podzolic soils in the southern States may have begun to develop as early as Kansan time. The Loveland loess, near Memphis, also has a well-developed profile in it, buried and beneath the Farmdale and Peoria loesses. Pleistocene geologists are not yet fully agreed on the correlations suggested here for the Memphis environs.

Following are abbreviated notes on the Peorian–Farmdale–Loveland (Illinoian) geologic section that overlies the Red-Podzolic soil mentioned above. Notes were kindly supplied by Dr. W. S. Ligon, Principal Soil Correlator for the Southern States. The location is one mile north of Memphis, Tennessee.

* Personal communication from R. W. Simonson and Guy D. Smith.

Exposures of Peorian, Farmdale and Loveland loess, one over the other.

Peorian. About 15 feet thick, calcareous unleached loess capped by 9 feet of leached loess in which Memphis silt loam is developed. Color of unleached loess (Peorian) is distinctly yellower than very pale brown, some distinct coarse mottles of light gray, and many faint mottles of light yellowish-brown. It is a slightly compact, smooth silt.

Farmdale. About 6 feet thick; no distinct profile developed. Material is leached silt, color pale brown to brown, with occasional streaks of very pale brown or gray; compact; hard when dry.

Loveland. Old B horizon is 3½ to 4 feet thick. Dominantly yellowish-red to red, intimately splotched with faint lighter and darker shades, and a few distinct grayish streaks; texture, silty clay loam to silty clay; hard when dry; medium coarse irregular blocky structure becoming platy when dry. Parent material is 20 feet thick. Strongly variegated; overall color is between yellowish brown and strong brown. Individual colors are yellows, light browns, and grays, of which only a few gray streaks of medium size are prominent. Slightly compact silt with low content of clay. Some soil scientists consider this to be part of the B horizon.

Strongly developed very old Reddish Prairie and Red Podzolic soils occur on some of the high terraces along the Arkansas, Canadian, and other rivers of Oklahoma and Texas. Lime has been leached to great depth in them; and, in some places, they have been buried by loess at least as old as the Peoria. Where no loess is recognizable, the high-terrace and upland surfaces probably have been exposed almost continuously since middle or early Pleistocene times with little change except those accompanying partial dissection.

Many areas of buried Yarmouth soils in Iowa, Missouri, Nebraska, and Kansas seem to have formed under poor drainage. Many have the characteristic sticky grey gley subsoil with rust-brown mottled characteristics of poorly drained soils. Some with claypan or planosolic character appear to have formed on nearly level surfaces, perhaps with fluctuating water-table, as can be seen a few miles north-east of Crete, Nebraska. These gumbo soils are developed both from Kansas till and from periglacial alluvium and loess.

Characteristically, the Yarmouth soil in Kansas till is leached of calcium carbonate, often to depths of 20 to 30 ft. (Kay and Apfel, 1928). The grey glacial till is streaked with dark brown and yellowish brown along a network of natural cleavage planes, both under buried soils with brown B horizons, expressing good drainage, and under the grey, sticky, Yarmouth gumbotil. The coloured streaks are 2 to 6 in. thick, and they extend to depths of at least 20 ft. in many places. From western Iowa to the western edge of the Kansas glacial till, many of the cleavage planes are lined with pure calcium carbonate, in some places cemented, in others a soft crypto-crystalline deposit from ½ to 2 in. thick. The white bands of calcium carbonate, paralleled by the brown and yellowish streaks, are orientated vertically in one axis; and they form a surface pattern, from above, of small polygons ranging from a foot or two to as much as 3 or 4 ft. across. Possibly the lime-filled cracks may have been opened by thin ice wedges during the time the Kansas ice was retreating and before soil formation had advanced very far. Perhaps frost

phenomena may have prevailed during one of the later glaciations. Deep drying and cracking seems unlikely on flat, marshy land, like that on which Yarmouth gumbo soils were formed.

The Sangamon soils

The soils of Sangamonian age are by far the most extensive of all of the strongly developed buried soils of central United States and probably of the rest of the country. Throughout their occurrence as far as we know them, the soils are deeply leached and strongly developed in presently humid areas, and leached to lesser depth in drier ones. On nearly level areas, as in southern Illinois and Indiana, drainage was poor in Sangamonian time and buried soils are of gumbo types with gley subsoils (Norton, 1930). However, in much of the area of Sangamon soils we find either dark or light coloured A horizons, with reddish-brown or strong-brown B horizons, that indicate good drainage. Much of the so-called 'Loveland soil' (more properly, Sangamon soil) in Loveland loess is of this kind. It was covered by Wisconsin-aged loess and the land was later dissected. Many so-called 'shoulders' on hill-sides mark the buried or partially buried Sangamon soils. Modern soils, then, are formed from Wisconsin loess and from truncated surfaces of the A, B, and C horizons of the Sangamon soil, plus glacial till or bedrock that may have been reached by dissection.

On the Great Plains, it appears from the dark-coloured A horizons and thick, reddish-brown clayey B horizons that the dominant vegetation probably was grass, and that the dominant well-drained soils were Reddish Prairie soils and reddish Chernozems with maximal textural contrasts between A and B horizons. However, eastward from eastern Nebraska and western Iowa, some of the buried Sangamon soils are podzolic and probably were developed under forest (Simonson, 1941). The profiles here have many characteristics in common with Grey-Brown Podzolic and Red-Yellow Podzolic soils developed under forest cover, and under climates warmer than present ones (Peltier, 1949).

Since the truncated buried soils occur in recently dissected areas, much of the modern soil on the dissected surface is thin. When the land is ploughed and farmed for a few years the dark modern surface soil is partly washed away and the exposed horizons of the truncated buried soil are clearly visible.

In ploughed and eroded hilly fields, between Mankato and Smith Center, Kansas, and near Red Cloud, Nebraska, the yellowish subsoil of the Hastings or Crete soils, developed in Wisconsin loess, shows clearly near the tops of the hill-sides; below that is exposed a broad dark band of the truncated Citellus zone (A horizon) of the Sangamon–Wisconsin soil; farther below is a broad band of the exposed brown or reddish-brown clayey B horizon of the Sangamon soil; and still farther down the slope there is either a yellowish or greyish outcrop of Loveland loess (see Fig. 3) or one of the underlying Cretaceous bedrocks. In eastern Nebraska a similar sequence usually grades into Kansas glacial till.

The authors examined and sampled a section exposed at the Yankee Hill Brick Plant, where Peoria, Farmdale (?), and Loveland loess, and

older Pleistocene sediments of less-certain age overlie the Fuson kaolinite clay of the Cretaceous.

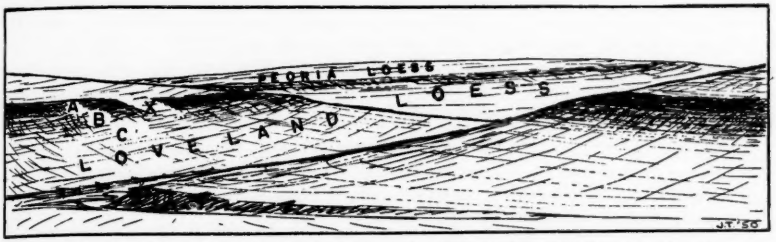

FIG. 3. Sketch of ploughed fields 6 miles north of Red Cloud, Nebraska, showing the Sangamon buried soil (A, B, and C horizons), developed in Loveland loess, cropping out below Peoria loess on hill-sides. X marks a place where the Sangamonian A and B horizons were truncated by a gully before the Peoria loess was deposited.

Section at Yankee Hill Brick Plant, just South of Pioneer Park, Lincoln, Nebraska

0–11 in. Granular, nearly black, A horizon of Crete silty clay loam.

11–44 in. Granular to blocky silty clay, B horizon of Crete silty clay loam. Lower part has small hard nodular lime concretions in some places in the cut. In other places there is no evidence of calcium carbonate accumulation.

44 in.–14 ft. 2 in. Leached Peoria loess. Pale brown (dry), to greyish-brown (moist), massive, soft, friable, non-calcareous heavy silt loam; coarse prismatic cleavage; numerous tiny pores; crotovinas numerous; small faint rusty specks in lower part.

14 ft. 2 in.–14 ft. 4 in. Upper Citellus zone (Farmdale loess?). Light brown (dry), to brown (moist), soft, friable, massive, heavy silt loam; crotovinas; pH 7·0.

14 ft. 4 in.–14 ft. 6 in. Upper Citellus zone. Brown (dry), soft, friable, massive, light silty clay loam; many crotovinas; pH 7·0.

14 ft. 6 in.–14 ft. 9 in. Upper Citellus zone. Brown (dry), to dark brown (moist), soft, friable, massive, light silty clay loam; crotovinas; pH 7·0.

14 ft. 9 in.–15 ft. 4 in. Upper, grading to lower Citellus zone. Mottled brown (dry), to very dark brown (moist), slightly hard, friable, weak-granular light silty clay loam; crotovinas; pH 7·6.

15 ft. 4 in.–16 ft. 10 in. Lower Citellus zone. A_1 horizon of Sangamon soil. Brown (dry), to very dark brown (moist), slightly hard, friable, weak-granular light silty clay loam; crotovinas; pH 7·6.

16 ft. 10 in.–17 ft. 4 in. Lower Citellus zone. Sangamon B_1 horizon. Mottled brown and very pale brown (dry), to mottled very dark brown and pale brown (moist), slightly hard, friable, weak-granular silty clay loam; pH 7·6.

17 ft. 4 in.–17 ft. 10 in. Degraded B_2 horizon of Sangamon soil. Mottled brown and very pale brown (dry), to mottled dark brown and pale brown (moist), hard, friable, weak, irregular-blocky, heavy silty clay loam; pH 7·6.

17 ft. 10 in.–19 ft. 10 in. B_{21} horizon of Sangamon soil. Strong brown (dry), to reddish-brown (moist), hard, friable, weak-blocky, light silty clay; pH 7·4.

19 ft. 10 in.–21 ft. 4 in. Probably A_1 horizon of early Sangamon (?) or Illinoian-age soil. Brown (dry), to dark brown (moist), hard, friable, weak coarse blocky, light silty clay; pH 7·4. This horizon appears to have been modified by illuviation from the overlying later Sangamon soil.

21 ft. 4 in.–23 ft. 2 in. B_2 horizon of early Sangamon (?) soil. Light brown (dry), to brown (moist), hard, friable, weak-blocky silty clay; pH 7·4.

23 ft. 2 in.–27 ft. 2 in. B_3 horizon of early Sangamon (?) soil. Light yellowish-brown (dry), to yellowish-brown (moist), slightly hard, friable, massive silty clay loam; pH 7·4.

27 ft. 2 in.–27 ft. 8 in. Weakly gleyed horizon of early Sangamon (?) soil. Mottled light brown and reddish-yellow (dry), to mottled brown and strong brown (moist), slightly hard, friable, massive silty clay loam; pH 7·4.

27 ft. 8 in.–28 ft. D horizon, early Sangamon soil. Mottled pale brown and light brown (dry), to brown (moist), hard, friable, massive, sandy clay loam; pH 7·4. Probably weathered Crete (Illinoian-age) outwash sand.

28 ft.–29 ft. Probably lower gley horizon of truncated Yarmouth soil. Mottled white and light brown (dry), to light grey and brown (moist), hard, friable, massive silty clay loam. Some black and very dark greyish-brown stains, probably iron and manganese oxides; pH 7·4.

29 ft.–37 ft. 2 in. Sappa silt (?). White (dry), to light brownish-grey (moist), with a few small, rusty spots, streaks, and stains. Soft friable massive silt loam; pH 7·0.

37 ft. 2 in.–42 ft. Yellow (dry), to yellowish-brown (moist), with thin, irregular, wavy bands of white and dark brown; soft, friable, massive, loamy fine sand; pH 6·8.

42–60 ft. Fuson clay (Cretaceous), a red, purple, grey and white mottled kaolinite clay; probably a remnant of a Cretaceous soil.

From central Nebraska the Peoria loess thins southward and southeastward. Near the Nebraska–Kansas line one can bore through the present soil and all of the Wisconsin loess to the Sangamon soil, within 10 ft. Still farther south, in southern Lyon County, Kansas, the Sangamon soil is buried only 18 in. to 2 ft. below the uneroded upland surface.

The Brady soil

As pointed out earlier, the Brady soil is developed in loess designated as Peoria and provisionally correlated as of Iowan–Tazewellian age (see Fig. 1). Following is a description of the Brady soil made 1½ miles south of Bignell, Lincoln County, Nebraska, near the original type locality (see Plate II).

0–4 ft. 4 in. Modern Chernozem soil. Mapped Holdrege very fine sandy loam.

4 ft. 4 in.–11 ft. Bignell loess. Light brownish-grey (dry) to dark greyish-brown (moist), massive, very soft, friable silt loam. Calcareous.

11 ft.–11 ft. 6 in. Transition horizon. Dark greyish-brown (dry) to very dark greyish-brown (moist), massive soft, friable silt loam. Contains secondary calcium carbonate leached down from loess above.

11 ft. 6 in.–12 ft. 8 in. A horizon of Brady soil. Dark greyish-brown (dry), to very dark greyish-brown (moist) weak-prismatic, friable silt loam that breaks easily to weak subangular blocks. Contains calcium carbonate in threads and films, leached down from material above.

12 ft. 8 in.–15 ft. B horizon of Brady soil. Pale brown (dry), to dark greyish-brown (moist), weak prismatic silt loam that breaks easily to weak subangular blocks. Contains numerous threads and films of calcium carbonate leached down from loess above.

15–20 ft. Peoria loess parent material. Light grey (dry) to greyish-brown (moist), massive, soft, friable, calcareous silt loam. Contains many fossil snails. Indistinctly spotted with strong brown.

Are Reddish Prairie soils relicts?

This leads us to consider the genesis of the Reddish Prairie soils of southern Kansas, Oklahoma, and Texas. When the term 'Reddish Prairie soil' was coined in 1938 (Baldwin *et al.*, 1938), the authors intended it to cover certain acid, grassland soils, with dark A horizons and red or reddish-brown B horizons, that seemed to be correlated with the sub-humid, warm-mesothermal climate of the south-central States. A complicating factor was that a large share of the soils in the Reddish

Prairie soils zone of Oklahoma are developed from red rocks which obscure any reddish colours that may have developed through soil formation. However, the older of the soils that have developed from non-red bedrocks and old terrace alluvium have redder A and B horizons than most of the Prairie soils of Nebraska, Iowa, and Illinois.

In the region of Reddish Prairie soils some of the clayey rocks have a large proportion of montmorillonite clay in them. On these the soils lack the reddish hues and do not properly belong in the Reddish Prairie group, even though they are in the Reddish Prairie soils zone. They differ little from the Prairie soils of north-central States.

Where a pre-Wisconsin land surface remains uneroded and without a blanket of Peoria loess, we usually find that the well-drained members of soil catenas have reddish-hued B horizons. This is true as far north as south-eastern Nebraska and south-western Iowa. The reddish-hued Sangamon soil can be traced out from under the Wisconsin loess along the Kansas–Nebraska border south of Wymore, Nebraska, and deep into Kansas. In some places the dark silty A horizon of the modern soil may be a small remnant of Peoria loess, but in others it seems likely that the modern soil is entirely a remnant of the soil that began to develop during Sangamonian time. We suggest that the Reddish Prairie soils, supposed to owe their colour to the warmer climate in which most of them are found, may actually owe their properties as much to their great age as to present climatic effects. Geologists have obtained evidence from the study of preserved vegetation and vertebrate fauna that the Sangamonian Interglacial climate was somewhat warmer and moister than that of the recent few thousand years. The warm climate may also have contributed to the redder colour of the soil.

Conversely, where we have traced Peoria loess as far south as Blackwell in northern Oklahoma, we have found that the B horizons of the modern soils are essentially no redder than the B horizons of modern soils in the cooler environment of Iowa, Nebraska, and the Dakotas. We must conclude, then, either that the post-Peorian climate has been too cool or that the time has been too short to produce a Reddish Prairie soil in Peoria loess at Blackwell.

Therefore we offer the hypothesis that the true Reddish Prairie soils may owe their colour and other characteristics more to their age and to former warmer climates than they do to the present climatic conditions under which they occur. If this hypothesis is reasonable, we shall have to re-examine our classification of the soils in the Reddish Prairie soils zone. If, as we expect, we can demonstrate that all the soils that began to develop from non-red materials during middle and late Wisconsin glacial time lack the reddish hues, we shall have to recognize that some true Prairie soils exist in the zone of Reddish Prairie soils.

Parallel with the occurrence of reddish soils in the zone of Prairie soils, and vice versa, are many examples of Chernozem-like and Chestnut-like soils with reddish-hued B horizons in the zones of Chernozems and Chestnut soils. In every case we know, these reddish hues are associated with relict or polygenetic soils which, for the most part, remain buried beneath Peorian loess.

Are Red Podzolic soils relicts?

We find a parallelism with the situation on the Great Plains in the loess belt east of the Mississippi River. The Memphis and Grenada soils are developed in Peoria loess southward from southern Indiana and Illinois almost to Baton Rouge, Louisiana. Soils of these two series have morphological characteristics more like Grey-Brown Podzolic soils than like the Red-Yellow Podzolic soils with which the greater part of them are associated. Marbut (1935) called attention to the fact that Memphis and Grenada soils belong in the Grey-Brown Podzolic group, and he attributed their presence in southern States to their relative youth.

Not only do the Grey-Brown Podzolic soils extend deep into the zone of Red-Yellow Podzolic soils, but old podzolized soils with reddish B horizons, resembling Red Podzolic soils, occur in southern Indiana, Ohio, and Pennsylvania. The Orleans silt loam of Washington County, Indiana (Miller and Higbee, 1939), is an example. Perhaps these old soils should be classed as Grey-Brown Podzolic soils of maximal development; perhaps they are relict Red Podzolic soils. Many of the old red soils of the Ohio Valley are buried beneath a thin mantle of Peoria loess.

Thorp and Smith (1949), who reported soils with morphology like the Grey-Brown Podzolic soils in Puerto Rico and in Assam, under humid tropical climates, ascribed the phenomenon to the relative youth of the soils. In other words, it appears that Grey-Brown Podzolic soils generally may be younger than Red-Yellow Podzolic soils, especially than the Red Podzolic soils like the Ruston, Orangeburg, and Cecil soils, where the two great groups are associated.

We have made many accurate determinations of soil colours, based on the Munsell Color Charts (Nickerson, 1941), in order to try to see what relationship may exist between soil colour and soils of various ages. Darkness and degree of chroma saturation vary from place to place, but the hues of modern soils developed in Wisconsin-aged loess, younger than Farmdale, are nearly everywhere no redder than Munsell 7·5 YR, and usually no redder than 10 YR. Exceptions are in a few places like southern Kansas, western Oklahoma, and northern Texas, where some of the eolian materials came from red rocks or red river sediments.

We think that a careful study of hue of parent materials compared to the hue of B horizons of zonal soils may eventually be used as a tool to help judge soil age.

Buried soils and soil fertility

Some buried soils have a bearing on the fertility of modern soils. In parts of south-eastern Nebraska and north-eastern Kansas where farmers have been ploughing the soil for at least 50 years, much surface soil, formed predominantly in Wisconsin loess, has been washed away. Erosion has exposed the reddish-brown B horizons of Sangamon and perhaps of the Yarmouth soils on many slopes. Corn planted on soils of this kind grows well where the dark surface soil remains intact; but the crop shows signs of nitrogen starvation and severe phosphorus deficiency where the reddish buried soils have been exposed. Where the solum has developed entirely from Peoria loess or from unleached Kansas till,

phosphorus deficiency in corn is less evident, even though there may be a shortage of nitrogen. Thus it appears that the Sangamon soil contains less easily available phosphorus than the modern soils, formed either from the Wisconsin-aged deposits or from recently exposed, but relatively little weathered, Kansas glacial till. Deficiencies of this kind make it very difficult to establish permanent vegetation for erosion control on eroded hill-sides.

Future work

Old soils, both exposed and buried, on the High Plains in south-eastern Colorado, south-western Kansas, western Oklahoma, and the 'Panhandle' of Texas need further study. We know that the Peoria loess thins south-eastward across the High Plains, from eastern Colorado, and that a buried soil with reddish clayey B and caliche horizons approaches the surface in the vicinity of Amarillo, Texas. This region is too complicated to be reviewed here. Here the Reddish Chestnut soils grade westward into the Reddish-Brown soils of the semi-arid southern steppes, and then to the Red Desert soils of truly arid regions. We may think of these older soils as relicts—essentially the products of former environmental conditions, but modified by the soil-forming factors of today.

Geologists, geomorphologists, and soil scientists have recently renewed their interest in Pleistocene geology and in its buried soils. We expect that co-operative studies, some of which are now in progress, will shed much light on the history of 'fossil' and modern soils, and will give us a better basis on which to evaluate the time factor in soil formation.

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A (*from top to bottom*). Modern soil, Crete silty clay loam, in Peoria loess; dark band is Sangamon soil with transition above to Peoria loess; dark band at level of man's head is probably early Sangamonian soil; the man is standing on the truncated Yarmouthian soil and silt; water stands on the top of the Fuson kaolinite clay, a truncated Cretaceous soil.

B. General view of the pit. Steam shovel is working at face of Fuson clay.

PLATE I. Clay pit at Yankee Hill Brick Plant, Lincoln, Nebraska

A. Brady soil, developed in Peoria loess and buried by Bignell (late Wisconsinian?) loess one and a half miles south of Bignell, Nebraska. Holdrege very fine sandy loam, the modern Chernozem at this site, has been truncated by recent erosion.

B. Sangamon soil developed in Loveland (Illinoian) loess and buried by Peoria loess, exposed in corn (maize) field, near Smith Center, Kansas. Note low scarp or 'shoulder' where Sangamon soil is exposed.

PLATE II

J. THORP, W. M. JOHNSON, E. C. REED
POST-PLIOCENE BURIED SOILS

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A PROVISIONAL CLASSIFICATION OF MALAYAN SOILS

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WITH PLATES 1 TO 3

Synopsis

A scheme for classifying Malayan soils is suggested tentatively, based on general observations at irregular intervals over a number of years, and not on a continuous detailed study of the characteristics and distribution of individual soil types. No schematic mapping has been done, but the soils chosen for sampling and analysis are representative of the most important soil groups.

The main factor on which the soil series are differentiated is soil parent material. The parent materials are classified broadly and the soils derived from these are described briefly. Tentative suggestions are made for the nomenclature of the soil series classified.

The soils are described mainly on the basis of morphological characteristics. A few analytical data are included. Brief reference is made to the potentialities of the soils judged chiefly on growth of rubber-trees. Views are expressed regarding the suitability of some of the more important soils for cultivation of other crops.

The relationship of Malayan soils to the recognized 'great soil groups' is discussed briefly.

Introductory

A DETAILED survey of Malayan soils has never been carried out and it is fully realized that, until this is done, any attempt at classifying the soils must be regarded as tentative. Where information is limited, approximations are often useful and it is perhaps desirable to record relevant observations even though they are admittedly inadequate to effect a complete system of classification of all Malayan soils. These observations have been made at irregular intervals over a number of years when opportunities arose to visit rubber estates in all parts of the country, not specifically for the purpose of classifying the soils on those estates, but chiefly to advise on problems relating to rubber cultivation and to conduct field experiments.

Geography and Climate

Malaya is part of the peninsula which extends southwards from Burma to Singapore. The distance from the northernmost boundary at Perlis to the southern tip at Singapore (latitude 1° 18′ N.) is about 700 miles and the country covers an area of about 51,000 square miles. Along the western and eastern sides of the peninsula are extensive alluvial plains extending inland for varying distances up to a maximum of 40 miles in the western plains and about 20 miles on the eastern side. From the coastal alluvial plains the country rises gradually through an intermediate band of foothills, which are extensively developed agriculturally, to a series of jungle-clad high mountain ranges running north and south, with valley troughs where agricultural development has proceeded more slowly.

Mean temperature and rainfall vary but little from year to year, and records for the year 1947 are given as an indication of the climatic conditions. Mean rainfall for the year was 110 in., with a minimum of 83 in. on the west coast and rising to a maximum of 169 on the east coast. The mean temperature was 80·7° F. with the limited range of 79·5° to 82·3° F. for ten stations; the mean maximum was 88·0° F. and the mean minimum temperature was 73·3° F. (Meteorological records for the hill stations, i.e. Fraser's Hill and Cameron Highlands, have not been included.)

*Geology**

The geological structure of Malaya is complex, but the main features may be summarized briefly as follows. Granite and other non-volcanic igneous rocks cover about half the total area. While most of the high mountain ranges are predominantly granitic, the range which includes the highest mountain (Gunong Tahan) is a notable exception, being composed mainly of upper Paleozoic or Mesozoic sedimentary rocks. The sedimentary rocks older than the granite occupy roughly a third of the total area. The major proportion of the remainder is covered with alluvium. Rocks younger than the granite are limited to very small areas of Tertiary sedimentary rocks.

The greater proportion of the developed land in Malaya is probably composed of soils derived from the sedimentary rocks older than the granite. Since these rocks must occupy an important place in any discussion of local soils, a synopsis of the lithological variation within this large group is given. They comprise:

(i) Triassic Formation: quartzite, shale, phyllite, schist with some chert and conglomerate.
(ii) Carboniferous and (?) Permian Formations: limestone, shale, phyllite, schist with some chert and quartzite.
(iii) Pahang Volcanic Series: Predominantly pyroclastic rocks with some lavas.

A little more than three-quarters of the surface of Malaya is covered with jungle or uncontrolled indigenous vegetation of one kind or another. Of the total area alienated for buildings, for agricultural development, and as mining land, more than half is planted with *Hevea*. It will be seen, therefore, that although observations recorded herein refer mainly to rubber land, they cover an appreciable proportion of the total area which must include soils derived from most of the important rock formations of the country. Soils derived from a few of the less important rock formations known to occur have not been located.

Basis for Soil Classification

A primary requisite in attempting to classify soils is to determine a suitable basis for classification. To this end we may consider which of the factors of soil genesis play the most important role in determining the morphological differences observed in the soil profile. The principal

* The writer wishes to acknowledge his indebtedness to the various publications of the Geological Survey Department, Federation of Malaya.

genetic factors are: climate, relief, parent material, time, and vegetation. The relative importance of each of these factors depends upon the scope and the purpose of classification. When considering the higher categories of classification of the soils of the world or a continent, climate and vegetation assume major importance, but over a small land area such as Malaya these genetic factors are fairly uniform. We are concerned here with establishing lower category units based on physical and chemical properties of the soils themselves, and the dominant factors which determine local variations in profile characteristics are relief, parent material, and time. Of these, parent material is undoubtedly the most important genetic factor and the most suitable basis for classification of local soils.

Some Malayan soils have been described and classified by Dennett (1929, 1932, 1933), Wilshaw (1932), and Hamilton (1936). Dennett (1929) recognized distinctions between soils formed from different parent materials but was content to classify parent materials into four main groups as follows: granite, quartzite, Raub family, and alluvium. Later on he (1933) adheres to the same broad classification, but to this list he adds the Highland Soils as well as those derived from the pyroclastic rocks of the Pahang Volcanic Series, and from dolerite. In attempting to subdivide these large groups, which are essentially based on a broad classification of geological formations, Dennett attaches more importance to the effect of topographical relief than to the effect of complex lithological variations within the broad geological groups he recognizes. In referring to the soils of the Raub family he distinguishes high-level soils and low-level soils; the so-called quartzite soils are subdivided into valley quartzites and general quartzites, while granitic soils are similarly separated into hill and valley soils.

The use of the terms 'Raub family' and 'Quartzite' for the parent materials of soils derived from rocks of the Carboniferous group and of the Triassic group respectively is unfortunate. Both terms suggest that the soil's parent material in each case has a fairly uniform mineralogical composition, or that the rocks included in each of the groups are lithologically similar. On the contrary, the soils which are included in each of the two groups are derived from a variety of rocks with widely different lithological characteristics. The name 'Raub Series' was first used by Scrivenor (1931) when he referred to the calcareous shales and allied rocks which are prevalent in the district around the Raub Australian Gold Mines. Later Scrivenor admits that it was a mistake to adopt this name and it was discarded. But the main objection to the use of the name in soil classification is that it may convey an erroneous indication of the nature of the parent material. The soils included are not calcareous nor are they necessarily derived from calcareous shales.

The use of the term 'Quartzite' in the sense that Dennett (1929, 1932), and later Hamilton (1936), used it is equally unfortunate, and perhaps even more so because the misuse of the name has gained currency in Malaya. One hears frequent reference to a quartzite soil when the soil may be derived from shale, phyllite, or schist. On sifting the evidence it would appear that the name 'Quartzite' has been used for all phases of the Triassic group of rock formation. The so-called quartzite soils

described in the literature cited are those derived from a complex variety of rocks recognized by the geologist as falling within the Triassic group. Quartzite forms one of the lithological variations, and as a parent material of soils is probably the least important. Of the soil types which fall within this group, the most widely distributed are those derived from shales, phyllites, schists, and sandstones. It is pertinent to note that quartzite nearly always weathers back into sandstone under the moist tropical conditions prevailing in this country.

Hamilton (1936) disposes of the soil parent materials under the headings granite, quartzite, limestone, Pahang Volcanic series, coastal deposits, and alluvium. Referring to granite soils he points out the difference between virgin and cultivated soils, but otherwise makes no distinction between types. Regarding the soils which he classes as quartzite soils, he appreciates that the rocks from which they are derived are very variable, so it is evident that he has in mind not only quartzite but other diverse beds forming the Triassic rocks; the use of the name 'quartzite' is therefore misleading. Hamilton discards the term 'Raub Series' but he substitutes the name 'limestone' when he evidently means rocks of the Carboniferous group. Soils derived from limestones cover relatively small areas in Malaya but soils derived from other quite distinct lithological variations of the Carboniferous group are widespread and are economically much more important.

The principle of using the parent material as a basis for classifying the soils has been accepted, but it is evident that previous workers in this field have adhered too rigidly to the broad classification of the geological formations as given in published geological maps, ignoring the complex lithological variations within each group which are clearly recognized in the field and are described in the memoirs published by the Geological Survey Department Federation of Malaya.

Parent Materials of Malayan Soils

The soil parent materials may conveniently be listed in the order of geological age, thus showing the possible variations within each geological age group as indicated on the published geological maps of Malaya.

Recent sediments. Alluvial deposits may be divided into two main groups: coastal deposits and inland alluvium. The coastal deposits consist principally of heavy clays and peat. The heavy clays of the western coastal belt form a distinct soil type quite different from the soils formed from inland alluvium. There are minor variations in texture and composition of the clay fraction, but for purposes of classification they are sufficiently uniform to justify grouping these together as one soil series. The writer is less familiar with the alluvial deposits on the east coast, but it is evident that the soils are more variable, sandy deposits occurring more frequently and covering larger areas in this region than in the west. It would seem, however, that the heavier soils of the east coast are similar to those in the western coastal belt, but pending further investigation they are regarded as a separate soil series.

Peat occurs as a deposit of variable depth over clay. In virgin jungle areas of the coastal belt the heavy alluvial clay is invariably covered by a layer of peat, varying in depth from a few inches to several feet. Development of such land for agricultural purposes results in exposure of this organic horizon, which then shrinks and is gradually extenuated by oxidative decomposition. Where the original peat horizon is shallow it disappears in course of time, so the existence of a transitional group of soils consisting of shallow peat over clay must be recognized. Areas of peat, several feet in thickness, do occur, however, but these have not been studied in detail.

Inland alluvium is much more variable than, and easily distinguished from, the coastal alluvial deposits. The former occurs at a slightly higher elevation and covers relatively large areas in the extensively developed intermediate belt between the coastal flats and the steeply rising terrain running along the centre of the peninsula. It covers, in particular, much of the area west of the Main Range where solid geology is shown on the geological maps as Carboniferous, and it contributes largely to the agriculturally developed land in parts of Perak and Selangor.

At this stage our knowledge of the inland alluvial deposits permits only for a classification of the soils into three main groups: (1) soils developed under conditions of impeded drainage; (2) free-drainage soils, loams, and clay loams with good permeability; (3) sands and sandy loams where drainage is excessive. Each of the three groups is regarded tentatively as one soil series but considerable variability is recognized, allowing for subdivision into several soil types.

Soils derived from recent deposits are classified as follows:

Parent material			*Soil series*	*Drainage*
Recent sediments	Coast deposits	Peat	Unclassified	Impeded
		Clay	1. Selangor Series (west coast)	Impeded
			2. Kelantan Series (east coast)	Impeded
		Sands	Sungei Buloh Series	Excessive
	Inland alluvium	Clays, loams	1. Perak Series	Impeded
			2. Chemor Series	Free

All soils developed on sandy deposits, whether they occur as lenticles in the coastal clay area or as part of the more irregularly distributed riverine alluvium, are provisionally classified as one group pending more detailed examination.

Igneous rocks (*post-granite, granite, and pre-granite*). The various soils derived from igneous rocks are widely different, depending on whether the parent material is basic or acidic. Soils derived from acid igneous rocks cover large areas in all parts of the country, while those derived from basic rocks are limited in extent, occurring locally in a few widely separated regions.

The group of acid igneous rocks consists of plutonic types, mainly granite, and volcanic types (andesites, rhyolites, &c.). Granite occurs over very large areas in all parts of the country and soils derived from granitic rocks probably cover a larger area in the aggregate than any

other soil. It is recognized that the solid formation varies considerably in mineralogical composition, but the final product of weathering appears to be fairly uniform, apart from variations in texture and the coarseness of the quartz grains. The coarse sand fraction is composed almost entirely of quartz. At this stage two soil series are recognized, one derived from fine- and medium-grained parent material (Rengam Series) and a less fertile, paler coloured soil derived from the coarse-grained phase of the granite (Tampin Series). The former is economically more important since it covers the major proportion of the total area of soils derived from granite.

Little is known about the soils derived from andesite, rhyolite, and other acid volcanic rocks since it happens that they do not occur to any great extent in the areas opened up for development. They are included in the classification because they are known to occur and are probably widely distributed in the jungle areas of Pahang and Kelantan.

Soils derived from basic igneous rocks, although limited in extent, are of particular interest and importance because they are the most fertile of all the sedentary soils in Malaya. Soils derived from the plutonic types of basic rocks have not been identified, but gabbro has been located in a few isolated areas by the geologists and a more detailed survey of the country will no doubt reveal the existence of more extensive outcrops of these rocks. Therefore provision has been made in this classification for including soils derived from plutonic types of basic rocks. Soils derived from volcanic types of basic rocks have been identified and examined. The largest consolidated area occurs in east Pahang. Here the soil is derived from basalt and has been provisionally named the Kuantan Series. In north Johore a deep friable red soil, derived from a basaltic lava, occurs over an area of several hundred acres. This is morphologically different from the Kuantan Series, and one is easily distinguished from the other by colour, texture, and structure. Chemical composition of the clay fraction also reveals differences between the soils. Performance on the two soils is equally good in so far as this can be determined from growth and yield of rubber-trees, but recognition of two soil series is justified on the basis of morphological characteristics.

Malayan soils derived from igneous rocks, therefore, are classified as follows:

Parent material			*Soil series*	*Drainage*
Igneous rocks	Acid rocks	Plutonic types (mainly granite)	1. Rengam Series	Free
			2. Tampin Series	Free
		Volcanic types (andesites, rhyolites, &c.)	Unclassified	
	Basic rocks	Plutonic types (e.g. gabbro)	Unclassified	
		Volcanic types (mostly basaltic)	1. Kuantan Series	Free
			2. Segamat Series	Free

Non-calcareous rocks of Triassic and Carboniferous age. For purposes of soil classification these two geological age groups are classified as one unit because a similar petrological sequence occurs in both groups. The non-calcareous formations of both Triassic and Carboniferous ages in

Malaya consist of sandstones, shales, phyllites, and schists. Soils derived from corresponding beds of Triassic and of Carboniferous ages are indistinguishable from each other; thus a soil derived from argillaceous rocks which fall in an area mapped by the geologist as Trias appears to be identical with a soil derived from shale of Carboniferous age. In this classification of local soils reference will be made to soil parent materials as sandstones, argillaceous rocks, and schists irrespective of whether they are of Triassic or Carboniferous age. Triassic rocks also include some coarse conglomerates. Soils derived from these are known to occur over limited areas, but these have not been examined. Provision is made in this classification for including soils derived from conglomerates.

In the published geological maps of Malaya the Trias formation is described briefly as consisting of quartzite and shale (a more detailed petrological description in the published literature includes phyllites, schists, and conglomerate). The omission of quartzite as a soil parent material needs explanation, especially since the term 'quartzite soil' has gained currency in Malaya. As a first step in the process of weathering in this country quartzite usually weathers back into a sandstone. Where quartzite occurs the solid strata immediately below the soil are usually sandstones. It seems logical therefore to regard the parent material of that soil as sandstone rather than quartzite.

The soils included in this section are probably more familiar to the casual observer than any of the other soils since they cover the major portion of the gently undulating terrain which lies between the coastal flats on the west and the steeply rising ground farther inland, a terrain which has been highly developed agriculturally and over which most of the major roads pass. In spite of easier facilities for examining these soils due to accessibility, considerable difficulties in classifying the soils have been presented by the complex variation, the interbedding of the solid formations, and the consequent merging of the products of weathering. Soils derived from essentially Triassic rocks and from lithologically similar beds of the Triassic and Carboniferous groups of rocks are classified tentatively as follows:

Parent materials		*Soil series*	*Drainage*
Trias and Carboniferous (non-calcareous rocks)	Conglomerates	Unclassified	..
	Sandstones	Kedah Series	Free
	Argillaceous rocks (shales, phyllites)	1. Batu Anam Series	Slightly impeded
		2. Malacca Series	Free
	Schists	Seremban Series	Slightly impeded

Calcareous rocks. Calcareous rocks consist of calcareous shales and limestones. The former lose their calcite by weathering, so presumably the soils derived from these would be indistinguishable from those derived from non-calcareous shales. No soil known to be derived from calcareous shales has been identified locally, and since it is unlikely that the calcareous nature of the parent rock would be perceptible in the final product of weathering, the soil being derived from the siliceous

portion of the rock, there seems little justification in recognizing these shales as a soil parent material different from the non-calcareous shales.

Limestone outcrops in several places, but it occurs usually as small hills rising abruptly from the plains. Soils derived from limestone are confined to a few yards around the base of these picturesque masses of pure limestone rising almost perpendicularly to an appreciable height above the general level of the surrounding country. The soils cover only a relatively small area in the aggregate, but, although not always suitable for rubber cultivation, they are very fertile and are particularly suitable for crops which can tolerate neutral and alkaline conditions. The soils examined are fairly uniform, varying slightly in intensity of red colour and reaction. They are grouped together provisionally as one soil series —the Perlis Series.

The classification of the parent materials of Malayan soils and the disposition of the various soils derived from these are summarized in the appendix. Inevitably there are a number of omissions. No doubt a more systematic survey of the soils will reveal a number of types which have not yet been identified, but there are others which have been observed and noted; because they are abnormal types which occur locally in relatively small areas, they have not been included in the classification. The occurrence of transitional soils of mixed origin on contacts of schist-granite and granite-limestone, &c., such as those described by Wilshaw (1932) for instance, is recognized, but they cover limited areas and are relatively unimportant. It may be of interest to report that podzolic soils have been located here, with morphological characteristics similar to those of the podzols in temperate countries. They have developed on light porous sands of alluvial origin, usually in depressions or on flat sandy terraces. In Malaya they are of academic interest rather than of agricultural importance.

Description of the Soil Series

Peat. Peat and peaty soils have not been studied in detail and no differentiation into soil series has been attempted on account of insufficient data. They occur in irregularly dispersed patches in the low-lying coastal alluvial expanse both on the west and the east coasts. In their natural state they are almost continuously submerged, and deep drainage is essential for successful development of peat areas for agricultural purposes. Rubber-trees grow well in these areas provided drainage is adequate, but difficulties have been experienced when rubber is planted on land which has been newly opened up. Not infrequently young rubber plants become moribund, or their rate of growth is severely retarded a few months after planting when their roots reach the water-logged horizon where toxic compounds are formed under the reducing conditions which exist. Symptoms of toxicity are more in evidence in areas where the peat is deep and where waterlogging occurs in the organic layer. When opening up virgin peat land it is sometimes advisable to cultivate shallow-rooting food crops for a few years as a preliminary to the establishment of the deeper rooting tree crops to allow for shrinkage and consolidation of the peat and to give time for a more thorough

investigation of drainage possibilities. In some areas at least this has been a customary procedure. It is of interest to note that Chinese squatters in peat areas often burn the surface horizon of peat as a preliminary to cultivation of food crops. This is done before the land is drained so that the depth of burning is controlled.

Although rubber-trees grow well on artificially drained peat, the yield of rubber per acre is seldom as high as that on the freely drained mineral soils. Moreover, the surface level of the peat is continuously being lowered, not only as a result of shrinkage due to progressively more effective elimination of surplus water, but also due to oxidative decomposition at the surface. Sooner or later the roots of trees are exposed. At best the root system is confined to a relatively shallow horizon and, with such a limited root hold, leaning trees are a common feature on peat land. The leaf canopy is usually heavy, which is to be expected on this type of land, so it is inevitable that appreciable losses of trees during wind storms do occur. No doubt peat areas are being exploited more successfully and to a better purpose when utilized for cultivation of shallow rooting economic crops.

Coastal alluvial soils. Alluvial soils are separated into two main groups generally referred to briefly as coastal alluvial clays and inland alluvial soils. The morphological characteristics of the former group of soils are fairly uniform although minor local variations are recognized. For instance, occasionally one comes across small patches, generally not more than a few acres in any one place, where a horizon of soil mixed with fragments of sea-shells occurs at, or close to, the surface, probably indicating an old beach. This horizon is seldom more than about 12 in. in thickness, but naturally it affects performance because of the marked difference in reaction of the medium. There are textural variations which must be recognized too, but over the major proportion of the flat coastal belt on the west coast the soil is a silty clay varying in colour from dark brown to blue-grey, depending on the amount of organic matter and on the level of the water-table. A typical sequence of colours in a soil profile is as follows: dark brown on the surface, brownish-grey immediately below followed by a horizon of brownish-grey silty clay with yellow and rusty mottlings, which in turn changes into blue-grey silty clay at lower levels. This permanently wet blue-grey horizon is very acid, and a pH of less than 3 is not uncommon. This brief description applies to the soils over the greater part of the coastal alluvial belt on the west coast, allowing for variations in depth and compactness of the different horizons. The name Selangor Series is tentatively suggested for this group of soils.

Less information is available regarding the soils of the east coast, but judging from general observations it would appear that sandy deposits form a much greater proportion of coastal alluvium in the east than in the west. However, the heavier soils developed under conditions of impeded drainage do cover quite large areas on the east coast as well, and they appear to have many characteristics in common with the Selangor Series. Until they have been examined in more detail, however, they are provisionally classified as a separate series for which the name Kelantan Series is proposed.

Soils of the Selangor Series are, potentially, the most productive soils of the country. With suitably controlled drainage and judicious management they grow most crops. When covered with vegetation they develop a fairly porous structure in the upper horizons in spite of their heavy nature, and this good structure is not impaired on exposure so quickly as that of the inland sedentary soils. Compared with other Malayan soils these heavy coastal alluvial soils have large reserves of plant nutrients. The contents of nitrogen and potash are high and available phosphate values, as determined by standard methods of analysis, are invariably higher than corresponding values for the inland sedentary soils, although low judging by the standards of soils of temperate countries. Little or no response to applications of fertilizers in experiments in young and mature areas of rubber on these soils has been detected. Nutrient deficiency is seldom a limiting factor to growth of rubber on the Selangor Series. Performance is determined almost invariably by the extent to which drainage conditions can be improved, but it is seldom possible to lower the permanent water-table sufficiently to achieve optimum conditions for rubber cultivation. The trees are usually very well grown, it is true, and carry dense green foliage, but the yield of rubber per unit area is invariably lower on these soils than on the freely drained inland soils. There is no doubt that these coastal alluvial soils are more suitable for shallow-rooting crops, and, if extension of land for food production is ever contemplated to cater for the needs of an increasing population, the possible development of these flat coastal areas for more intensive cultivation with food crops merits careful consideration. Here are large areas of highly productive soils which, with careful management, are capable of producing good crops for many years without resort to fallow resting to restore structure and fertility.

Cultivation of food crops in tropical soils is a special problem which is outside the scope of the writer's work and therefore cannot be discussed in detail, but it is a problem which no one who is interested in the potentialities of the soils can afford to ignore. The possibility of inter-cropping food crops in rubber areas has been considered from time to time and arising out of this problem the suitability of different soil types for cultivation of short-term food crops has been considered. The effects of cultivation of crops which give inadequate protection to the soil are well known. Loss of soil by erosion is the most serious factor, but the principles of soil conservation methods are well known; with careful management, the harmful effect of erosion can be reduced considerably, although measures taken are seldom completely effective. What is often not fully realized is that tropical soils deteriorate on exposure even though loss of soil by erosion is prevented. The organic matter in the surface soil is soon lost by oxidation and the structure of the soil is rapidly impaired, both of which result in a lower status of fertility. The harmful effects of erosion, oxidation, and loss of structure become apparent more quickly when the soil is mechanically disturbed by digging or ploughing. Some soils deteriorate more quickly than others. Of the local soils, those derived from schists are probably the worst in this respect and are the least suitable for cultivation of food

crops, especially those crops the harvesting of which entails mechanical disturbance of soil. Soils derived from argillaceous rocks (shales and phyllites) also deteriorate fairly rapidly on exposure. Granitic soils are intermediate, while the most stable of the inland soils are those derived from basic rocks. The latter are eminently suitable for cultivation of food crops provided effective measures are taken to control erosion. Unfortunately these soils cover a relatively small area and cannot contribute much to any scheme for large-scale food production. If the other inland soils were utilized for continuous cultivation of food crops, provision would have to be made for reafforestation within a few years to restore structure and fertility. The re-establishment of forest growth may take several years unless a rotational system of cropping is followed, designed so as to prevent the establishment of lalang (*Imperata arundinaceae*) as an ecological sequence in the change from cultivation of economic crops to forest fallow. This might be possible if the rotation ends with the cultivation of a vigorous tree crop.

Taking all factors into consideration, it would seem that the coastal alluvial flats would be the most suitable for intensive cultivation of food crops if the need for this should become urgent. The area available is large, the soils are fertile, water is abundant and, with suitable drainage, the supply can be controlled to suit most crops.

Inland alluvial soils. Inland alluvium is of mixed origin and consequently the soils developed on this transported material are very variable. Detailed classification of these mixed deposits has not been attempted, but three main groups may be recognized: (1) soils developed under conditions of impeded drainage; (2) free-drainage soils, loams, and clay loams with good permeability; (3) sands and sandy loams where drainage is excessive. The first two groups resemble the inland sedentary soils rather than the coastal alluvial soils. Morphological characteristics of the first group are similar to those of soils derived *in situ* from argillaceous rocks, while soils of the second group are comparable to the sedentary soils derived from more arenaceous rocks. In performance, and in response to manuring also, they resemble the inland sedentary soils rather than the coastal alluvial soils.

Alluvial sands are in a class apart. They have quite distinct morphological characteristics and are in no way similar to the reddish-yellow soils derived *in situ* from sandstones. These sandy alluvial sediments, whether they form part of the large expanse of marine alluvium or of the more scattered areas of inland alluvium, are provisionally grouped together as one soil series.

Soils developed under conditions of impeded drainage are silty clay loams, the colour of the surface horizon is mainly grey with yellow mottlings. This lies over blue-grey silty clay loam at varying depths below the surface. These soils are lighter in texture and generally less impervious than the coastal alluvial silty clays (Selangor Series). Artificial drainage is essential for successful cultivation of most crops, especially rubber, although not to the extent that this is necessary on the lower lying and heavier soils originating from marine alluvium. Topography varies from flat to very gently undulating. Rubber-trees grow well

on these soils provided drainage is adequate. Nitrogen and potash contents are medium to medium-high, while phosphate content is invariably very low. Rubber-trees on these soils usually respond to manuring. Ironstone concretions in the solum are not common, although they do occur occasionally, distributed irregularly in small pockets or as a thin band at varying depths below the surface. The name Perak Series is tentatively suggested for these soils.

Free drainage soils of alluvial origin are yellow to reddish-yellow in colour, varying in texture from sandy loams to clay loams; laterite concretions are usually absent. They resemble the more widely distributed freely drained sedentary inland soils and for purposes of making recommendations for manuring of rubber-trees they are classed together. Nitrogen content is low to medium, phosphate content is invariably low, and potash content is variable. These soils are provisionally called the Chemor Series.

Bedded sands and sandy gravel transported by streams form terraces which are drier and on a higher level than the more recent alluvium. The soils developed on these sandy deposits vary from coarse-grained loamy sand to fine-grained sandy loam. Drainage is excessive. Growth of rubber usually reflects a low status of fertility and response to manuring is generally well marked. Nitrogen, phosphate, and potash contents are very low, and treatment with a complete fertilizer is usually recommended at all stages of growth of the rubber-trees. These soils are provisionally grouped together as one series—the Sungei Buloh Series.

There is evidence to suggest that most of these alluvial sands are podzolic in character. In a few areas one or all of the A_0, A_1, and A_2 horizons are clearly seen, changing into compact brownish-yellow light sand (B horizon) at lower levels. In one place a thin layer of cemented and lustrous iron oxide on top of the B horizon was clearly observed. These are abnormalities, however, since they occur only in very small patches and, locally, they are of little importance agriculturally. The majority of these loose sandy soils show no clearly defined zonation apart from a darkening of the surface 2 or 3 in. by organic matter. Then it changes abruptly into pale yellow or pale brownish-yellow sandy material often with irregularly distributed patches of more compact, dark brown or ferruginous coloured sand. The yellow horizon, with or without the dark brown patches, is usually deep, reaching to a depth of 5 ft. and often deeper. The clay fraction separated from samples of one profile examined has a very low silica-sesquioxide ratio. Analytical data are shown in Table 1.

TABLE 1

Horizon	*Clay* %	*Organic carbon* %	*pH*	*Clay fraction* SiO_2/R_2O_3
0–3 in.	6·6	1·08	5·5	0·33
3–8 ,,	9·7	0·57	5·5	0·28
8–14 ,,	9·8	0·31	5·3	0·21
14–24 ,,	10·3	0·20	5·3	0·22

It is probable that this soil is the relict of an illuvial horizon, the eluvial layers having been lost by oxidation and erosion.

Soils derived from acid igneous rocks. Only soils derived from granitic rocks have been identified and examined. These cover very large areas in all parts of the country. Soils derived from volcanic types of acid rocks occur only in limited areas, at least in the developed parts of the country, but they may be more widely distributed in the jungle areas of Pahang and Kelantan where these volcanic rocks are best developed.

The depth to which granitic rocks weather varies considerably, but usually the soil is very deep. According to Scrivenor (1931) the average depth to which granite weathers is about 30 ft. 'Core-boulders' which resist weathering are common but seldom sufficiently abundant to interfere with the exploitation of the land. The high mountain ranges are predominantly granitic, but most of this area is too steep for cultivation. The gently sloping foothills, however, have been extensively developed.

The soils derived from granite are classified into two series. One of these, the Rengam Series, covers the major proportion of the total area of granitic soils. Soils of this series which are derived from fine- and medium-grained parent material are reddish-yellow, friable, sandy clay loams, often micaceous. Occasionally a gradual change from yellow to yellow with red mottling, and finally to a uniform pale red colour, can be observed within 6 ft. from the surface, but usually the uppermost reddish-yellow horizon is much deeper. The pale reddish hue at lower levels is typical of the product weathered from granite. Concretions of ironstone have not been observed in these soils.

The performance of the Rengam Series is good judging by the growth of the rubber-trees, and even in old rubber areas or in replanted areas severe physical deterioration of the soil is not apparent except that the surface soil has a tendency to pack and form a hard impermeable crust on exposure. Where structure and natural fertility of the soil have been impaired, it usually reflects the effect of previous cultivation with other crops, the planting and harvesting of which entailed frequent mechanical disturbance of the soil. Evidence of this is seen in several districts, particularly in parts of Negri Sembilan and Malacca where food and other short-term crops were extensively cultivated during the latter half of the last century in land which has since been planted with rubber-trees. Nevertheless, even in these previously cultivated areas the degree of deterioration is appreciably less in the granite soils than in those derived from argillaceous rocks and from schists.

As in most other inland soils, the nutrient status of the Rengam Series is by no means high. Nitrogen and phosphate contents are low while potash content is medium-low to medium. The better performance of the Rengam Series compared with some of the other inland soils reflects better physical condition rather than a more abundant reserve of nutrients. Texture and structure are good and the soil is deep, friable, and permeable, allowing for easy absorption and free movement of water. Rubber-trees on these soils respond to treatment with nitrogen and phosphate, but response to treatment with potash has not been demonstrated. It would appear that most of these granitic soils contain reserves

of potassium adequate for normal development of rubber-trees, much of which is probably present in the form of unweathered potassic minerals.

The second soil series recognized, the Tampin Series, is derived from coarse-grained highly siliceous granitic rocks. The soil is a coarse-grained sandy loam, whitish-grey at the surface changing into pale yellow below. A characteristic feature is the high proportion of very coarse sand consisting mainly of quartz with some mica. No laterite concretions have been observed. Drainage is free to excessive. The soil is clearly less fertile than the Rengam Series, and in performance it is only a little better than the sandy alluvial soils (Sungei Buloh Series). The Tampin Series covers relatively small areas and because of its limited distribution it has not been examined in detail. No manuring experiments have been sited on it, but it is expected that, like the Sungei Buloh Series, it will respond to regular and fairly frequent applications of a complete fertilizer.

Soils derived from basic igneous rocks. Only soils derived from volcanic types of basic igneous rocks have been identified and examined. Although limited in extent they are conspicuous, not only because of their rich, distinctive colours but also because of the luxuriant growth of crops planted on these soils. They are the most fertile of all inland soils in Malaya and it is to be hoped that much larger areas occur in the unexplored jungle land.

Two soil series are recognized, both of which are derived from basaltic parent material and are equally productive, but each of the two series has distinct morphological characteristics and one is easily distinguished from the other by colour, texture, and structure. Moreover, the chemical composition of the clay fractions of the two soil series is different.

The Kuantan Series, which is well represented in east Pahang, is a dark reddish-brown loam over clay loam, very friable and permeable, with a distinctive, fragmental structure. It is very deep, and to a considerable depth is uniform in colour, texture, and structure. Small laterite concretions may be distributed irregularly in the solum and sometimes a more or less continuous band of rounded concretionary ironstone may occur at lower levels. Roots of rubber-trees are well distributed throughout the profile to a depth of several feet, a feature which is not common for Malayan soils. Nutrient content is relatively high except for 'available' phosphate as determined by the Truog method which is low, but phosphate extracted by HCl (1 : 1) is high. Furthermore, the contents of nutrients fall with increasing depth below the surface much more gradually in this soil than in all other inland soils derived from acid and intermediate rocks. The composition of the clay fraction is different from that of all other soils examined in that percentage SiO_2 is exceptionally low ($\pm$10 per cent.) and percentage of Fe_2O_3 is exceptionally high (over 30 per cent.). It naturally follows that the silica-sesquioxide ratio is very low. Analytical data are shown in Table 2.

The Segamat Series, which has many characteristics in common with the Kuantan Series, is a deep brownish-red heavy clay, friable and permeable; it has a mildly developed crumb structure, contains no gravel or laterite concretions, and is uniform in colour and texture to at least

TABLE 2

Horizon	Clay %	Organic carbon %	pH	Clay fraction SiO_2/R_2O_3
0–3 in.	25·2	3·13	5·1	0·26
3–6 ,,	48·4	1·95	5·2	0·25
6–12 ,,	54·9	1·35	4·9	0·21
12–24 ,,	56·7	0·90	5·1	0·21

15 ft. Roots of rubber-trees are well distributed to a depth of about 6 ft. Performance on this soil is excellent; trees are very large and yields of rubber are generally high. Values for organic carbon and plant nutrients are comparable with those of the Kuantan Series except that the phosphate extracted by HCl (1 : 1) is even higher. Composition of the clay fraction, however, reflects certain fundamental differences between the two soil series. Percentage SiO_2 is much higher and percentage Fe_2O_3 much lower in the Segamat Series. Analytical data are shown in Table 3.

TABLE 3

Horizon	Clay %	Organic carbon %	pH	Clay fraction SiO_2/R_2O_3
0–3 in.	65·6	2·07	5·0	1·39
3–6 ,,	73·7	1·44	5·1	1·38
6–12 ,,	71·4	1·32	4·9	1·38
12–24 ,,	68·3	1·02	4·8	1·34

Soils derived from Triassic and Carboniferous sedimentary rocks

1. *Sandstones.* Soils derived from sandstones are reddish-yellow friable sandy loams, the depth of which varies depending on elevation and/or hardness of the underlying strata. Shallow soils, however, are not common; they are limited to the upper parts of the steeper hills where erosion has been active. The soil is a type which is easily eroded and is particularly unsuitable for crops the cultivation of which entails disturbance of, or gives inadequate cover to, the surface soil. This soil series may be classed as a good type exhibiting characteristics which are favourable for successful cultivation of rubber and other tree crops. The soil is loose and permeable, but drainage is not excessive. As in most other local soils, the clay content gradually increases with depth and the lower horizons are slightly more compact.

Analytical data for a soil derived from sandstone are shown in Table 4.

TABLE 4

Horizon	Clay %	Organic carbon %	pH	Clay fraction SiO_2/R_2O_3
0–4 in.	18·8	2·20	4·4	2·09
4–12 ,,	21·3	0·56	4·7	1·87
12–18 ,,	23·1	0·45	4·6	1·94

2. *Argillaceous rocks.* These include shales and phyllites. Two distinct soils series derived from these beds are classified (Batu Anam Series and Malacca Series), although it is realized that these may not include all the soil types developed under varying conditions on these argillaceous rocks. The shales show a fairly consistent type of weathering resulting in a fairly uniform product, but it is admitted that less is known about soil development over phyllites. It will be appreciated that identification of the parent materials of soils is often difficult in the tropics because of the great depth of weathering, especially of the softer rocks. However, these two parent materials are provisionally grouped together since there is evidence to show that both, under certain conditions, may give rise to soils which have many characteristics in common.

The Batu Anam Series is a soil which covers fairly large areas in all parts of the country on undulating and hilly land, but is best developed in strongly rolling country. Texture and colour vary within a restricted range, but in the main it is a yellow to brownish-yellow silty clay loam over mottled silty clay. At the top of the mottled horizon the dominant colour is yellow with darker yellow and grey mottling; as the partly weathered parent material is approached, grey becomes the dominant colour. Occasionally a narrow band (about 2 in.) of rounded concretionary laterite occurs at varying depths below the surface, but this is not a consistent feature of the soil profile. Fragments of quartz, the relict of a quartz vein in the parent rock, may also occur in the solum. Drainage is slightly impeded, but artificial drainage is never necessary. The soil is capable of good performance. Although compact, the upper part of the soil profile is fairly friable when covered with vegetation, and allows for easy penetration of roots, but it deteriorates rapidly on exposure. Rubber-trees on this soil usually respond to treatment with nitrogen and phosphate. Content of potash determined after extraction with HCl (1 : 1) is generally rather high, although values for exchangeable potash show considerably more variation. Analysis of the clay fraction indicates a feebly lateritic development. It is interesting to note the slight fall in the silica-sesquioxide ratio of the clay fraction of the horizon immediately below the narrow band of laterite. Analytical data are shown in Table 5.

TABLE 5

Horizon	*Clay* %	*Organic carbon* %	*pH*	*Clay fraction* SiO_2/R_2O_3
0–4 in.	31·3	1·84	5·2	2·68
4–12 ,,	38·7	0·53	4·5	2·08
12–24 ,,	47·9	0·27	4·5	2·19
24–26 ,,	Rounded concretionary laterite			
26–36 ,,	58·6	0·19	4·6	1·90

The Malacca Series occurs almost invariably on flat or very gently undulating terrain and usually at a lower elevation than the Batu Anam Series. This may be significant when considering the conditions favourable for the development of this particular soil type. A characteristic

feature of this soil series is the high percentage of ironstone or laterite. The proportion of gravel, which consists almost entirely of laterite concretions, may amount to 80 per cent. or more of the total weight of gravel plus matrix. The ironstone is also characteristic in that it is deposited as rounded but irregularly shaped concretionary gravel (globular concretions are not common) or occasionally as a hard slag-like mass. Both forms may occur together in the same area. The concretions vary in size up to about 1½ in. in diameter. The laterite horizon is loose at the top but more compact in the lower horizons. The matrix varies from a very friable yellow or brownish-yellow loam to a sticky reddish-yellow clay. The lower horizons show slight mottling, sometimes grey and sometimes bright reddish-brown. The laterite horizon is covered by a layer of friable yellow or brownish-yellow loam to clay loam free from gravel, varying in depth, but is seldom greater than about 12 in. Growth of rubber-trees is very variable, depending largely on the depth of soil above the laterite and on the mechanical composition of the matrix. Where the laterite concretions are loosely packed and the matrix is a friable loam, roots penetrate easily and are often well distributed to a depth of about 6 ft. In such areas a stand of well-grown trees may be established successfully, but performance generally is well below the standard for most other soils. Analytical data for a typical example of the heavier phase of the Malacca Series are shown in Table 6.

TABLE 6

Horizon	*Clay* %	*Organic carbon* %	*pH*	*Clay fraction* SiO_2/R_2O_3
0–7 in.	49·2	1·70	4·8	1·59
7–12 ,,	62·1	0·98	4·6	1·65
12–24 ,,	71·0	0·69	4·5	1·55
24–36 ,,	70·8	0·35	4·8	1·68

It has not been possible to ascertain with certainty the identity of the parent material of this soil. The evidence suggests that it is developed usually, but possibly not invariably, over phyllites. According to Scrivenor (1931) the greater part of the laterite in Malacca territory occurs over phyllites. Pending further investigations this laterite soil is classified as a soil derived from argillaceous rocks without further qualification, although the writer is of the opinion that soil in which the presence of laterite is a dominant feature is not likely to have developed over the shales.

3. *Soils derived from schists* show a number of minor variations, but since only a broad classification into units is intended, they are grouped as one series—the Seremban Series. The dominant characteristics of the soils are sufficiently uniform to justify this, but the minor variations are not entirely ignored and allowance is made for subdivision into soil types.

Schists weather into a soft mass in which foliation is preserved and frequently observed on examination of the lower horizons of the soil

profile. Immediately above this partly weathered parent material are fragments of ironstone or laterite having the same flattened structure. It would seem that these fragments have been formed in the incompletely weathered zone by displacement of the rock minerals by iron, retaining at first the original foliated structure of the rock and gradually increasing in thickness by further deposition of iron to form the roughly flattened ironstone fragments usually associated with soil derived from schists. Whatever the mode of formation of the laterite in this soil, the shape and structure of the fragments are characteristic of the soil type and quite distinct from the rounded concretions in the Malacca Series. Size and texture of the solid fragments, as well as their position relative to the surface, are extremely variable. A feature of the Seremban Series is the presence of quartz veins, often disintegrated and partly decomposed, which again are found at variable depths. Colour and texture of the soil vary within a restricted range, but yellow is the dominant colour and usually the soil is a sandy clay loam or sandy clay over clay. The clay horizon immediately below the ironstone fragments is frequently pale grey with rusty-brown mottlings. The upper part of the solum is friable and permeable while the clay below is sticky and impervious. Where this soil has been under cultivation for several years, there is ample evidence of severe erosion in the past and the present surface soil is doubtless exposed subsoil. The heavier phase of this soil series exhibits signs of impeded drainage close to the surface as a result of deterioration after cultivation and exposure. Performance is naturally very variable, depending largely on previous history of cultivation. In the virgin state it exhibits no unfavourable characteristic, and is capable of good performance provided its natural structure and permeability can be maintained. It is a soil which deteriorates rapidly on exposure.

Some analytical data for a typical example of the Seremban Series are shown in Table 7.

TABLE 7

Horizon	*Clay* %	*Organic carbon* %	*pH*	*Clay fraction* SiO_2/R_2O_3
0–3 in.	23·7	1·37	4·8	1·72
3–9 ,,	27·9	0·74	4·7	1·84
9–21 ,,	34·3	0·37	4·7	1·82

Soils derived from limestone. These soils are of very limited extent; they occur over a restricted area, seldom more than a few hundred yards in width, around the base of limestone cliffs in Selangor, Perak, and Perlis. The soil, provisionally called the Perlis Series, is a very friable dark reddish-brown loam over more compact clay loam. Colour is uniform to a considerable depth. No laterite concretions have been observed in the soil profiles examined. The soil is very fertile; the pH ranges from 6 to about 8·5, and the more alkaline phase of this soil series is not suitable for the cultivation of rubber. Nutrient status is comparatively high, although the content of readily available phosphate

(determined by the Truog method) is invariably low. Some analytical data for a soil derived from limestone are shown in Table 8.

TABLE 8

Horizon	*Clay* %	*Organic carbon* %	*pH*	*Clay fraction* SiO_2/R_2O_3
0–3 in.	21·2	2·28	6·2	0·63
3–6 „	22·6	1·28	6·1	0·62
6–12 „	26·8	0·88	6·1	0·61
12–24 „	24·8	0·75	6·2	0·60

Relationship to 'Great Soil Groups'

It is of interest to consider how the local soils, which we have grouped into lower category units, could be arranged into higher categories—the 'great soil groups'. Several systems of classifying world soils into higher category units have been proposed. The scheme outlined by Marbut and developed by the United States Soil Survey workers appears to be the most acceptable. This is based on the concept of zonality, showing relationships existing between soils and the climatic and ecological environments under which they have developed. A further elaboration of this scheme for classifying soils of tropical and equatorial regions has been suggested recently by Kellogg and Davol (1949). Consideration of the characteristics of Malayan soils leads to the conclusion that these are similar or very closely related to typical examples of the categories Kellogg and Davol describe, and it would appear that the major soil types of Malaya could be grouped conveniently in the higher categories of classification which they propose. It is considered that Malayan soils would fall within the following categories:

1. Zonal Soils	Reddish-brown Latosols	Kuantan Series
		Segamat Series
		Perlis Series (?)
	Yellow Latosols	Rengam Series
		Tampin Series
		Seremban Series
		Batu Anam Series (?)
	Yellow Podzolic	Sungei Buloh Series
2. Intrazonal Soils	Ground Water Laterite	Malacca Series
	Wiesenböden (?)	Selangor Series
3. Azonal Soils	Alluvial Soils	Perak Series
		Chemor Series

Latosols. Kellogg suggests this new term for soils which he describes as 'having their dominant characteristics associated with low silica-sesquioxide ratios of clay fraction, low base exchange capacities, low activities of the clay, low content of most primary minerals, low content of soluble constituents and a relatively high degree of aggregate stability'. These soils are lateritic in the sense that lateritization is in progress and an immaturely developed laterite horizon may be found in the profile, but they are distinguished from laterite soils in that the presence of a

laterite horizon is not a dominant feature nor is it an essential characteristic.

The majority of Malayan soils fall in this group. Those derived from basic rocks have characteristics which fit in with those classified as Reddish-brown Latosols. They are porous clay loams varying in colour from a rich brownish-red to reddish-brown; they have a well-defined structure, some fragmentary and others crumbly. In some of these soils a narrow band of concretionary laterite occurs at varying depths below the surface.

Soils derived from the more acid and siliceous rocks have a high proportion of yellow in the colour pattern. Typical colours are reddish-yellow (7·5 YR 6/8),* brownish-yellow (10 YR 6/6), yellow-brown (10 YR 5/4), and pale yellow (5 Y 7/3). They have all the essential characteristics of latosols and may be classified as Yellow Latosols. Their physical and chemical properties suggest close resemblance to the soils of the Belgian Congo described by Kellogg except that Malayan soils have even a lower content of soluble constituents and are probably less productive. The Yellow Latosols of Malaya appear to have a higher proportion of yellow in the colour pattern than the corresponding soils of Belgian Congo. This may be due to the fact that the former have been developed under more humid conditions (mean annual rainfall about 110 inches) or because they have been derived from more acid or more siliceous parent materials.

Ground Water Laterite. Accepting that the term 'laterite' should be confined to the materials which consist of hard concretions of iron and aluminium oxides, or slag-like masses, or softer ferruginous-bauxitic material which hardens on exposure, and accepting also that the term 'laterite soils' should be confined to those in which the presence of laterite is an essential and dominant feature, only one of the soil series recognized (the Malacca Series) can be classed as a laterite soil. The evidence suggests, however, that in most cases the laterite has been formed under the influence of a fluctuating water-table. Soils of the Malacca Series have developed usually, although possibly not invariably, over argillaceous rocks, and this implies the existence of an impervious horizon at the lower levels. It may be significant to note that these soils are found almost exclusively on flat or gently undulating ground at fairly low elevations. Furthermore, in most of the areas examined the lower horizons are distinctly mottled. Therefore it would appear that these soils have characteristics usually associated with Ground Water Laterites. In some areas evidence of a fluctuating water-table is absent within 6 ft. from the surface, although a similar deep horizon of indurated iron oxide has been formed, but one must assume that the typical mottling usually associated with a fluctuating water-table may occur at a much lower level. Nevertheless, the writer is not certain that a deep horizon of hardened laterite will not be formed except under the influence of a fluctuating water-table. Narrow bands of concretionary gravel are common and have been observed at varying depths below the surface in freely drained

* Symbols for hue, value, and chroma of colour according to the Munsell system of colour notation.

soils where the horizons above and below these bands of hardened laterite are identical in colour, texture, and structure, distinctly porous, and with no trace of any characteristic indicative of a fluctuating water-table. Even so, it is admitted that general observations lead one to the conclusion that laterite has developed in greater abundance either in, or immediately above, a medium in which water movement is or has been restricted, and may have been formed when the permanent water-table was much higher than it is now.

Alluvial soils. The character of the alluvial soils depends largely on their source and on local conditions of drainage and vegetation. The Selangor Series has well-developed characteristics reflecting the dominant influence of the nature of the parent material and drainage. Therefore it would seem that these may be classed as intrazonal hydromorphic soils rather than azonal soils. In the virgin state under forest they may have characteristics resembling Half Bog soils, but they are rapidly altered by cultivation, exposure, and the effect of artificial drainage. There are transitional soils in which a shallow dark brown peaty material overlies grey and mottled clay, but most of the soils included in the Selangor Series have a profile which appears to fit more closely the description given for Wiesenböden.

The inland alluvial soils have little profile development and it would seem that they may be classed as azonal soils.

Conclusion

The provisional character of the classification proposed cannot be too strongly emphasized. The suggestions put forward are not the outcome of a systematic survey of Malayan soils but of general observations made when opportunities arose to examine soils in several widely scattered places. The writer is fully conscious of many shortcomings and omissions. While parent material is undoubtedly the most important genetic factor in determining the characteristics of local soils, it is realized that the effect of relief is probably insufficiently emphasized. Also the effects of cultivation and erosion in altering the character of the soil profile have not been sufficiently stressed. Erosion has been prevalent, resulting in the production of truncated or immature soils. Until a detailed survey of the soils of the country is carried out the importance of these factors in determining the character of local soils cannot properly be assessed.

Acknowledgements

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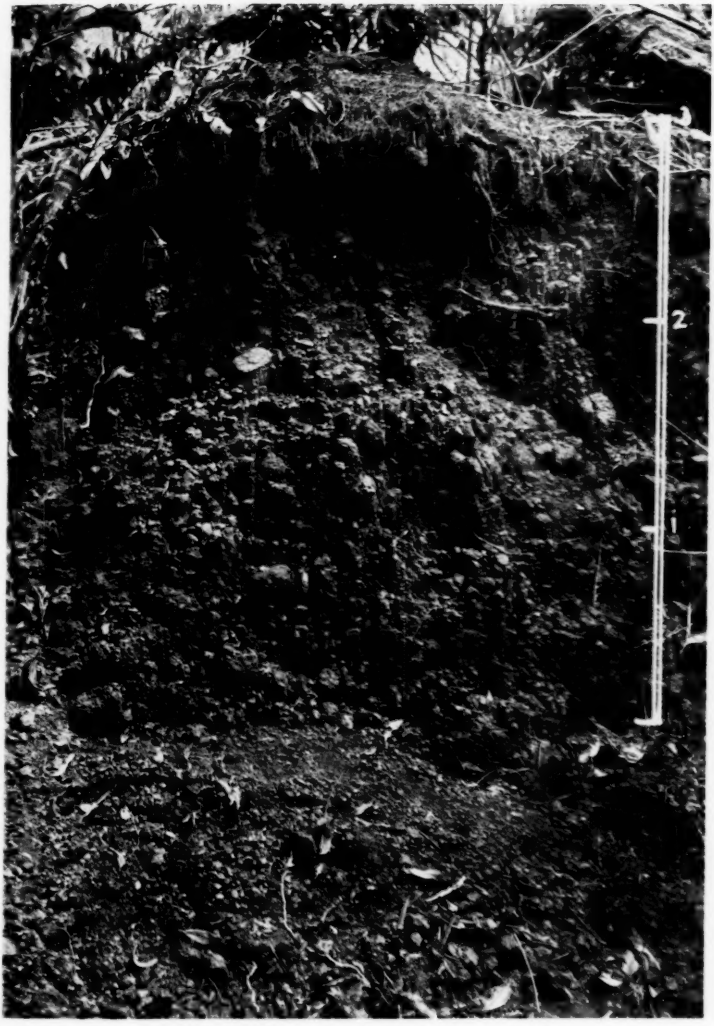
APPENDIX

Provisional Classification of Malayan Soils and their Parent Materials

	Parent material		*Provisional series name*	*Drainage*	*Remarks*
RECENT SEDIMENTS	Coast Deposits	Peat	Unclassified	..	..
		Clay	1. Selangor Series	Impeded	Clays in the western coastal belt.
			2. Kelantan Series	,,	Heavy soils of the eastern coastal belt.
		Sands	Sungei Buloh Series	Excessive	Includes lenticles of sand in the coastal alluvium as well as river-borne sands.
	Inland Alluvium	Clays and loams	1. Perak Series	Impeded	Soils developed under conditions of impeded drainage.
			2. Chemor Series	Free	Freely drained loams and clay loams. No laterite concretions. Relief flat or gently rolling.
IGNEOUS ROCKS	Acid Rocks	Plutonic types (mainly granite)	1. Rengam Series	Free	Soils derived from fine- and medium-grained rocks.
			2. Tampin Series	,,	Soils derived from coarse-grained phase of granite rocks.
		Volcanic types, (andesites, rhyolites, &c.)	Unclassified	..	..
	Basic Rocks	Plutonic types (e.g. gabbro)	Unclassified	..	..
		Volcanic types (mostly basaltic)	1. Kuantan Series	Free	Reddish-brown soils. Highly ferruginous. Some laterite concretions in the lower horizons.
			2. Segamat Series	,,	Brownish-red heavy clays derived from basaltic lava. No concretions.
MESOZOIC AND UPPER PALEOZOIC NON-CALCAREOUS ROCKS	Conglomerates		Unclassified	..	..
	Sandstones		Kedah Series	Free	Reddish-yellow sandy loams. Relief undulating and hilly.
	Argillaceous Rocks (shales, phyllites)		1. Batu Anam Series	Slightly impeded	Yellow to brownish-yellow silty clay loams. Mottling at lower levels. Some laterite concretions.
			2. Malacca Series	Free	High proportion of rounded laterite concretions a dominant feature of these soils.
	Schists		Seremban Series	Slightly impeded	Sandy clay loams over silty clay. Flattened and platy lateritic fragments and a vein of quartz are characteristic features of these soils.
UPPER PALEOZOIC CALCAREOUS ROCKS	Limestone		Perlis Series	Free	Dark reddish-brown clay.

(*Received 26 June 1950*)



1. Laterite soil near Sungei Buloh, Selangor. Profile showing laterite concretions. Surface as it appears after exposure for several weeks.

2. Laterite soil near Sungei Buloh, Selangor. Upper side of a terrace cut for planting rubber plants on sloping ground showing bed of concretionary laterite. Surface as it appears after exposure for several weeks.

3. Laterite soil near Sungei Buloh, Selangor. Profile exposed in a freshly dug pit. Laterite blocks dug out of the pit shown in top right-hand corner.

SOME AGRICULTURAL PROPERTIES OF CEYLON MONTANE TEA SOILS

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WITH PLATE

SOME of the oldest and most valued tea in Ceylon grows on the plateau and the eroded slopes of the highest of the three peneplains of Archaean rocks which form the mountain massif of the island (Adams, 1930). The third peneplain averages 6,000 ft. in altitude, at which elevation there still remain restricted areas of grassland locally known as *patanas* which were of much greater extent before the establishment of tea. Patana land exists on both sides of the watershed, that on the west receiving the rain of both monsoons (SW. and NE.); that on the east of the north-east monsoon only. On that account there are wet patanas, dry patanas, and transitional types. The soils discussed in this paper refer particularly to the first and last kinds.

The wet patanas have as their dominant species a tall tufted grass (*Chrysopogon zeylanicus* Thw.). According to the latest of several conflicting views about this ecological formation, patanas are regarded as an edaphically conditioned pre-climax, or occasionally as a retrogression caused by periodical burning on the part of villagers seeking grazing ground for cattle (de Rosayro, 1945).

Ceylon tea soils as a whole frequently have ill-defined profiles, but the patana soils are quite distinctive. To a depth of 18 in. to 2 ft. there is a dark humus-laden horizon full of grass roots. Beneath this there is a gravel pan, typically about 3 in. thick, which follows the contour of the land. Below is a very large soil volume of red-brown soil (laced with quartz seams and gradually merging into soft weathered rock; Plate 1). The photograph shows a profile exposed on a building site. The mode of formation of the pan is in doubt, but it has all the appearance of an erosion pavement submerged by soil creep.

The root growth of tea is effectively impeded by this gravel pan and its underlying subsoil unless, in the operation of planting, the layer is pierced; or until more vigorously rooting shade-trees perform a similar function. Because of this root weakness (Mann, 1933) tea planted on patanas usually takes a long time to become successfully established.

Water Stability

The wet patana soils receive annually between 75 and 125 in. of rain. When planted in tea they are exposed to the full violence of this precipitation in the early years of cultivation, and owing to the periodic pruning and weeding, further periods of exposure are of regular occurrence. Despite these unfavourable circumstances the humus horizon on carefully cultivated soils has persisted for at least a couple of generations.

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This is due to the remarkable water stability of this soil, a stability that is also shared by the horizons containing but little humic matter.

The separation of soil aggregates by sieving in water as described by Keen (1933) and used for tropical soils by Martin (1944) showed that nearly 60 per cent. of the soil remains on the sieves in aggregates whose size is conventionally regarded as contributing to good soil structure (Table 1). Since sieving technique is subject to much variation it should be stated that, to obtain these results, soils were wetted overnight on porous dishes and that the percentages retained on the sieves were corrected for the sand and gravel contained in each fraction.

The reproducibility of the results is excellent.

TABLE 1

Percentage Weights of Soil retained on Sieves after Wet Sieving

Sieve dimension . . .	10-mesh	20-mesh	40-mesh	*Total*
% retained	23·5	19·2	14·5	57·2
S.E. (means of 3) . .	0·91	0·18	0·44	0·71

The same characteristic of water stability is shown when the soils are examined by Childs's (1940) technique of moisture-characteristic curves.

A typical example is shown in Fig. 1. The curves I, II, and III represent the differential curves dv/dp obtained when water is withdrawn from a soil under varying degrees of pressure deficiency. The three curves refer to successive wettings and dryings of the same soil. Unlike the soils used by Childs, the maxima show no shift towards higher equilibrium-pressure deficiencies, and there is no flattening of the modes. The interpretation is that the soil aggregates have not been broken down by the 'artificial weathering' of alternate wetting and drying, their particle size ($>$ 1 mm. $<$ 2 mm.) distribution has not been randomized, and by analogy the distribution of the radii of curvature of the moisture films has not been substantially altered.

To this remarkable water stability these patana soils owe their high resistance to erosion and their character of being immediately cultivable without structural damage almost immediately after heavy falls of several inches of rain *per diem*.

Carbon and Nitrogen Status

The climate at which these soils exist is reasonably temperate. At the Tea Research Institute on the slopes of the third peneplain (altitude 4,500 ft.), the 15-year averages for monthly air temperatures show the following range: maxima 69·8° to 77·6° F., minima 54·7° to 60·4° F. Ground frosts are occasional. The contents of carbon and associated nitrogen are accordingly high. These soils have a characteristic organic profile. The diminution of carbon content with depth is shown in Fig. 2.

The values are derived from the mean of six samples. The curve of best fit is logistic in type.

A noticeable feature of these soils is that their carbon-nitrogen ratios are higher than those in temperate zones. McLean (1930) has previously

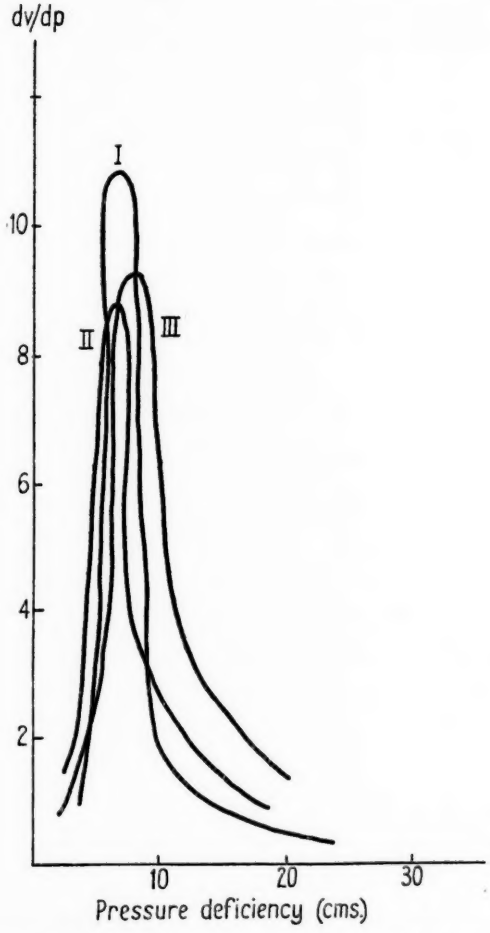

FIG. 1. Soil water withdrawal maxima after successive wettings.

remarked on similar high values in tropical soils examined by him and has drawn attention to their divergence from Jenny's (1928) generalization based on a series of American soils that at high temperatures the C/N ratio narrows. These results are in accordance with McLean's. Table 2 gives data derived from a carbon-nitrogen survey of experimental areas that had been under tea cultivation for varying periods. The number

of composite samples taken varied according to the number of plots in the experiment and is recorded for each set. Because the areas from which the time series is derived are not identical, there is no strict proof that cultivation under tea has actually changed the carbon-nitrogen ratio,

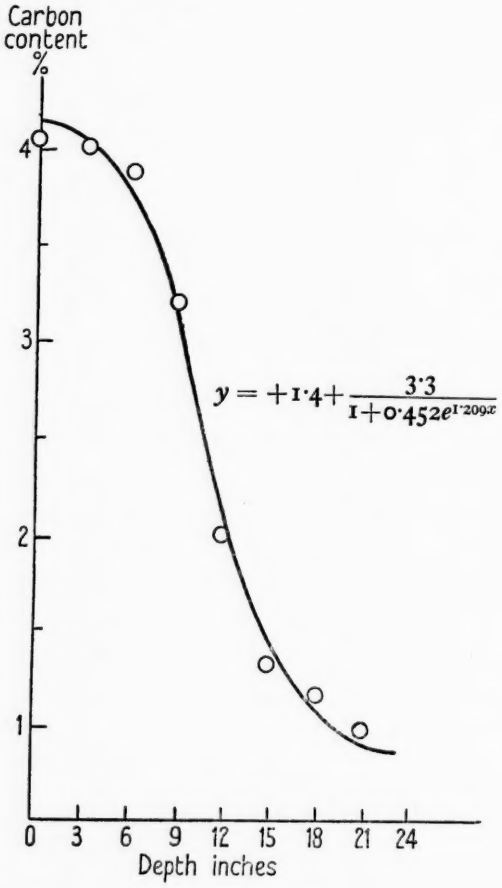

FIG. 2. Variation of soil carbon with depth.

but the data suggest that such is the case. Cooper (1946) has shown that the continual incorporation of tea prunings into a soil does increase its nitrogen content. The field records show that these areas have been receiving over the stated terms of years, large though unspecified quantities of leaf from tea prunings and green-manure loppings. The diminution of C/N ratio seems to reflect a change in the nature of the carbon-nitrogen linkage due to this policy.

TABLE 2

Carbon, Nitrogen, and Organic-Matter Content of Patana Soils (St. Coombs) per cent.

Period of cultivation	*No. of samples*	C	N	*Organic* matter*	C/N
Nil (virgin patana) .	25	5·79	0·320	9·98	18·1
10 years . . .	32	5·71	0·320	9·84	17·8
13 years . . .	27	7·58	0·436	13·07	17·4
20 years . . .	48	7·58	0·469	12·79	15·8
50 years (estimated) .	54	6·31	0·468	10·88	13·5

* Robinson's factor (1949).

Response to Fertilizer Nutrients

Routine soil analyses for N, P, and K have given little help in assessing the agricultural productivity of these patana soils, but field experiments have shown unmistakably the need for nitrogen and phosphoric acid as a condition of economic crop yields.

Nitrogen

The high values of nitrogen in Table 2 are deceptive when considered as indicators of high fertility. In a soil well colonized by tea roots it is seldom possible to find more than a trace of nitrate nitrogen. The low availability of nitrogen is particularly noticeable when first the land is broken up and for several years afterwards, although this is the period when normally an accession of nutrient from decomposing vegetation would be expected. In field experiments extending over a period of 15 years these soils have shown a linear relationship between yield and nitrogen application up to 80 lb. of nitrogen per acre per annum. When the crop is in full production after pruning the average regression coefficient over the period is 4·5 lb. of crop (dry weight) for each lb. of nitrogen supplied.

Phosphoric Acid

The responses to phosphoric acid in the same series of experiments are less spectacular. Additions above 30 lb. per acre P_2O_5 have failed to give a response. During a period of 12 years the average response to phosphate has been 2·5 lb. of crop dry weight per lb. of P_2O_5 applied in the form of superphosphate.

The distribution of this added phosphate in the soil is of some interest. It is commonly assumed that soils of high sesquioxide content immobilize phosphoric acid. These soils contain an average of over 40 per cent. of clay in the top soil and 50 per cent. in the subsoil and in this clay the R_2O_3 percentage is 48. Table 3 gives the phosphoric-acid content of top soil (0–12 in.) corresponding to the depth of cultivation, and subsoil (12–24 in.), as determined in the hydrochloric-acid extract after the experiments had been in operation for 12 years.

TABLE 3

Phosphoric-Acid Contents of Patana Soils (HCl *extract*) *mg.* P_2O_5 *per 100 g. Soil*

Added P_2O_5 *lb. per acre*	*Nil*	*30*	*60*
0–12 in.	90	101	107
12–24 in.	81	87	93

The regressions of soil phosphate on amount added are substantially linear in both top and subsoil, showing that the effect of application has penetrated uniformly below the level of cultivation. The type of cultivation carried out does not involve the inversion of the surface layer on which the fertilizers are distributed.

Not only has the phosphate penetrated the soil but its efficacy remains high for a considerable period in terms of the crop responses produced. Table 4 gives the dry weight of annual weeds grown, between rows of tea 4 ft. apart, during the period 4 March to 6 July 1948.

TABLE 4

Yield of Weeds due to Phosphatic Manuring of Different Duration
Lb. Dry Weight per Plot

	Series A	*Series B*	*Difference*
P_{30} . . .	43·3	29·9	13·4
P_0 . . .	12·2	10·7	1·5
Response . .	31·1	19·2	..

Series *A* received P annually from 1934 to 1947.
Series *B* received P annually from 1934 to 1944.

The results show that the behaviour of the P-deficient plots is similar, the difference between the two yields being without statistical significance. The phosphate-treated plots give a response of 275 per cent. on the continuously manured *A* series and on the *B* series whose phosphatic treatments ended 4 years before the weeds were allowed to grow, there was still a response of no less than 160 per cent. These remarkable responses are in keeping with those recorded by Barbier, Chabannes, and Marquis (1948) who contravert the assumption that because fixation of phosphate occurs, as defined in empirical chemical terms, it must necessarily imply an inability on the part of the plant to use such metamorphosed nutrient.

Conclusion

The data here presented refer to a number of soil characteristics that have been encountered during *ad hoc* investigations on soil management at a commodity research institute. The writer has severed his connexion with Ceylon, and there is accordingly no opportunity to follow up the empirical observations which show distinct deviations from widely accepted conceptions of tropical-soil properties, and for that reason it has been thought worth while to put them on record.

Patana soil profile.

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THE EVALUATION OF SOILS AND THE DEFINITION OF QUALITY CLASSES FROM STUDIES OF THE PHYSICAL PROPERTIES OF THE SOIL PROFILE IN THE FIELD

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Summary

THE relative productivity of certain soil series has been determined from an evaluation of certain physical characteristics of the soil profile which are measurable in the field. The evaluation has been based on the assumption that the most important physical properties of a soil affecting its productivity are its texture, its depth, and the goodness of its drainage.

The basis of the evaluation formula is that a rating is given to each textural class, ranging from 20 for a medium loam to 3 for a gravel and 5 for a heavy structureless clay, and this rating is given for each inch down to the bottom of the profile, or to an arbitrary depth of 30 in., whichever is the shallower. These ratings are added together to give a textural value, V, for the soil. If there is any gleying in the top 30 in. this value is then reduced by multiplying by a factor G, which is less than unity and which is smaller the higher the top of the gley horizon. The yield of wheat, P, as measured by the weight of ears produced per unit area at any spot in the field was calculated by the formula $P = cVG$, where c is an arbitrary constant. This prediction formula accounted for 90–7 per cent. of the variance of the wheat yield in 1947, a year in which accurate estimates of the yield were made, but only 68 per cent. of the variance in 1948, a year in which the yield figures were subject to large errors. The formula was less satisfactory for the yield of straw.

The formula $P = cVG$ was more accurate than $P = cV_G$ where V_G is the textural value to the top of the gley horizon, a result interpreted as showing that wheat roots make some use of gleyed soil.

In most English-speaking countries some system of soil classification has been evolved in which the chief unit of study is the soil series. The description of a soil series varies a little in the different countries, but all systems make use of the soil profile as the criterion on which the soil character is established and the series differentiated.

A major difficulty becomes at once apparent when soil-series maps are studied, viz. the degree of soil variation allowable within the series. Attempts have been made to overcome this by the use of subdivisions called phases, which may be said to consist of those physical variations within a series or type which do not justify segregation into a new series or type. Though such divisions are the result of field observation and careful study, they are of necessity purely arbitrary and there is no truly quantitative method for their differentiation.

Again, the soil series, being defined usually by a place-name, does not give an indication of the soil's quality. From time to time various systems of soil, site, and environment classifications have been evolved to overcome this difficulty, but in the main they have been too subjective to withstand practical criticism. In certain other countries attempts have been made to arrive at some more certain method for the differentiation of soils into quality groups.

The investigations of which this paper is a brief report have been the particular study of the author since 1939, and were designed to attempt to evaluate the major physical attributes of the soil profile and to determine to what extent such characteristics as texture, depth of soil, and quality of drainage affected the inherent productive quality of the soil. In any region with a well-defined system of farming the potential yield of the constituent crops will largely be determined by the climate and management coupled with the characteristics of the different soils. Since the object of the investigation is the study of the physical properties of the soil, sites had to be selected on which the effects of both climate and management were uniform and could be discounted.

For this purpose a large field was selected on the junction of the Oxford Clay and Cornbrash formations so that the soil throughout the field was as variable as possible while the management was carefully controlled for uniformity over the whole area. It was assumed that the climate for the area was also uniform.

Methods for the Assessment of Soil Values

The basis of the evaluation is in essence that of the German *Bodenbonitierung*, and the estimate is built up by the awarding, on a scale basis, values for certain soil characteristics which are diagnosable in the field. Normally laboratory investigations have only to be made to prove field diagnosis. It has generally been held that the most important soil attributes which affect crop productivity and can be measured in the field can be grouped under three main headings, namely

(*a*) *Soil texture*. The expression 'texture' defines the relative amounts of the coarse and fine inorganic material of the soil mass.

(*b*) *The depth of the soil*. This is the depth to which active root development most commonly may be detected and extends for this purpose to a maximum of 30 in.

(*c*) *The goodness of drainage*, measured by the depth at which partially anaerobic conditions commonly develop some time during the year, and which may be diagnosed in the field by the various characteristic forms of gleying.

In any system of grading based on judgement rather than on direct measurement, the ability to pick out the extreme is relatively easy to acquire, but the correct assessment of the intermediate grades initially rests on an integration of experience and observations that can come only from long field experience or good teaching. In land classification and soil survey there is little difficulty in determining 'very good' and 'very bad' fields or soils, but the problem of grading the less extreme types has

been constantly under review since these investigations commenced, so that the earlier work which has led up to the scales of grading now in operation need not be discussed, though it must be borne in mind that none of these scales is fortuitous, but each one is the result of several years of study.

The Soil Characteristics

For the purpose of evaluation, soil-profile pits are dug to a depth of at least 30 in. (except where circumstances do not permit, e.g. shallow soils on rock). The choice of 30 in. for a pit is to some extent arbitrary, but repeated observation of profiles in arable soils has shown that few visible roots of arable crops are normally to be found below this depth. In forest-soil investigations pits are made very much deeper.

The details of the soil profile are recorded on the Field Soil Description Sheet of the Soil Survey of England and Wales, and samples of each horizon are removed in case further investigation in the laboratory is required.

The Estimate of Texture

The soils are grouped into the broad textural types recognized by the Soil Surveyors' Conference of the Soil Survey of England and Wales. The basis of grading has been of a combination of 'feel' and inspection of the soil mass at 'field-moisture content' in the field.

The soils are given a scale of grading as shown in the following table.

Field diagnosis	*Symbol*	*Scale of grading*
Gravel	G	3
Light Sand	Sa	8
Heavy Sand	Sb	14
Light Loam	La	16
Medium Loam	Lm	20
Heavy Loam	Lb	18
Light Silt	Za	15
(Medium Silt	Zm	12)
Heavy Silt	Zb	6
Clay a	Ca	15
Clay b	Cb	5

Attention may be drawn to the clays. It was found in practice that there are at least two different kinds of subsoil clay, one, which is called 'Ca', being composed of well-defined good structural aggregates with well-defined porosity, and another, 'Cb', which is massive and tenacious with little or no visible pore space—i.e. structured and structureless clay material, respectively. It may also be useful at this point to explain that the major differences between a laboratory measure of texture and a field measure lies in an estimation of two different soil properties. In the field, texture is the 'feel' of the mineral particles in their natural state of aggregation, whereas the laboratory determination is made on the dispersed phase of the material after stones, organic matter, and carbonates have been removed. The scale of grading, therefore, though called 'texture' does in field diagnosis make some allowance for the 'structure' of the material as well. In order to obtain some quantitative value for

field 'feel' a method of mechanical analysis consisting of a simple water disintegration may be used. The method consists of boiling a 10-g. sample of air-dried soil with distilled water for half an hour. The fractions are separated by decantation and weighed air-dry to the first decimal of a gramme. No peroxide or acid is used in the method. The following table gives the range over which the various 'field textures' vary in these particular investigations.

Texture grade	*Texture value*	*Texture range in %*		*Texture ratio*
		Silt and clay	*Coarse and fine sands*	
Sa	8	30	70	$> 2{\cdot}3$
Sb	14	30—35	70—65	2·3—1·8
La	16	35—45	65—55	1·8—1·2
Lm	20	45—55	55—45	1·2—0·8
Lb	18	55—65	45—35	0·8—0·5
Ca	15	65—80	35—20	0·5—0·25
Za	15	65—80	35—20	0·5—0·25
Cb	5	80	20	$< 0{\cdot}25$

The standard sample of Cb (blue clay) used in these investigations had a ratio of 0·20.

Since the profile pit is dug to a depth of 30 in. and since the texture of the soil will generally vary with depth, it is necessary to obtain an estimate of the texture value over the whole 30 in. of profile. The technique adopted to determine this has been to measure the depth of each distinct soil horizon, multiply each horizon depth by the appropriate texture value, and sum these together.

Thus a soil consisting of equal depths of La over Lb over Ca would possess a profile texture value (V) of 490.

Depth × *Texture rating*	$D \times T = V$
10 × 16 (La)	160
10 × 18 (Lb)	180
10 × 15 (Ca)	150
	490

Where soils are shallower than 30 in. and they have been derived from the *in situ* disintegration and weathering of underlying limestone rock it has been found, solely by experience, that a balancing factor should be introduced. Thus if the 'rock' horizon consists of a mixture of rubble-rock and soil particles (as it always does), then the rating for this horizon is taken as one-third of the texture rating of the soil material forming the matrix and is calculated to the arbitrary 30-in. depth of the standard profile. Thus a compensation is made for the shallowness of the soil on disintegrated limestone. No such compensation is needed if the shallow soil overlies solid rock pavement.

The Estimation of the Drainage Factor (G)

It is understood that for a given soil profile variations in the drainage or water régime can modify the agricultural value of the whole soil mass.

The field diagnosis of the adequacy or otherwise of drainage is based on the following observations.

i. *Perfect drainage.* No mottling at any point in the 30-in. profile implies 'perfect' or 'excessive' drainage. 'Perfect' drainage implies that water moves easily through the profile, but is retained in sufficient amount for normal plant growth but in insufficient amount to cause mottling or to restrict free aeration. 'Excessive' drainage implies that water moves too rapidly through the soil and insufficient of it is retained for the normal plant growth of all species other than those in truly ecological equilibrium with it.

ii. *Imperfect drainage.* The presence of oxidized yellow and/or brown ochreous mottling implies a tendency for water to be held rather longer in the soil mass at certain periods of the year than in a perfectly drained soil and insufficiently long for serious anaerobic mobilization of iron to take place. There is essentially a zone of fluctuation of air and moisture, both through and around the structural aggregates.

iii. *Impeded drainage.* The presence of the bluish-green, self-coloured, shiny material known as true gley implies a very high water-holding capacity for the greater part of the year with a reduction in aeration to an anaerobic environment in which all reactions are of a reduction nature. Such conditions are generally, but not necessarily, associated with heavy clay soils.

The marking values for the drainage of the whole soil mass is based on 'perfect' drainage, 'imperfect' drainage in the absence of true gley being marked as unity. 'Impeded' drainage is diagnosed by the depth in inches at which true gley appears and is marked or evaluated as a decimal of unity.

True gley at	9–12 in.	Drainage factor 0·5
	13–15 in.	0·6
	16–18 in.	0·7
	19–24 in.	0·8
	25–30 in.	0·9
Perfect drainage		1·0

So far, experience has shown that in ordinary arable fields gleying at a shallower depth than 9 in. does not occur, so that the factor 0·5 is considered to be the lowest limit for the scale compatible with reasonable arable practice.

The Profile Value

This is assessed from the formula

$$\text{Texture value } (V) \times \text{Drainage factor } (G) = \text{Profile value}$$

If the example quoted on page 53 be now supposed to possess a gleyed zone at 27 in., the profile value becomes

$$490 \times 0{\cdot}9 = 441.$$

The validity of this method for allowing for the effect of gleying upon yield was further investigated by comparing the accuracy of prediction, using this value with that obtained by using the textural value V_G com-

puted for the profile down to the top of the gley horizon. The basis of this second calculation is the assumption that ordinary arable-plant roots do not generally develop in gleyed soil.

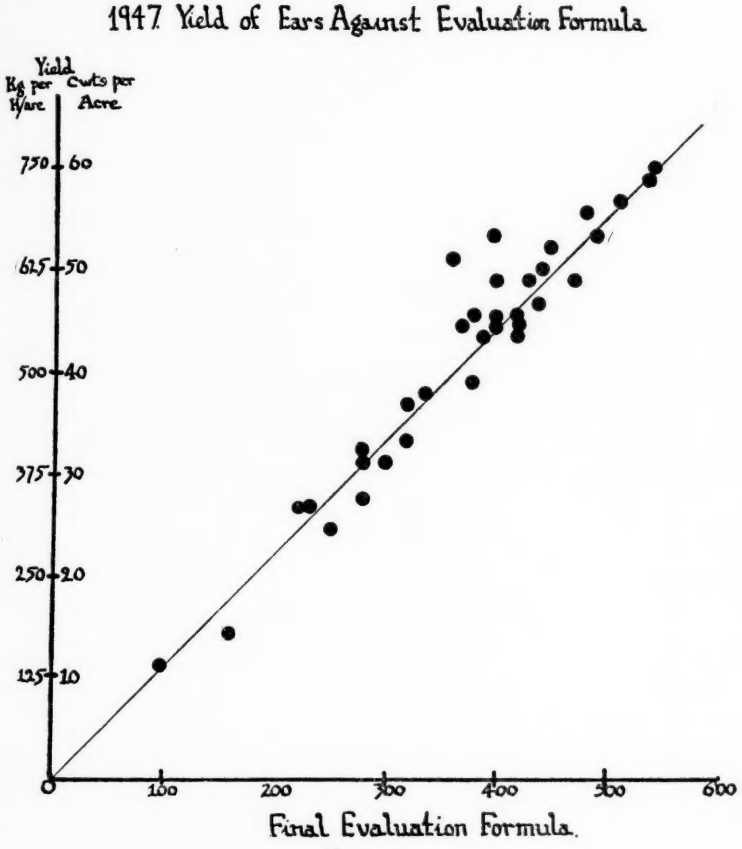

FIG. 1.

Experimental Method

The quantitative evaluation of potential productivity in so far as it is affected by the physical character of the soil profile was carried out as follows. The field sampling was done during the harvests of the two years 1947 and 1948. Fifty quadrats each of 25 sq. ft. were randomized over a heterogeneous soil site of 20 acres and then every stalk of wheat within the quadrats was cut as close to the ground as was possible and made into a sheaf. After the sheaves had acquired a uniform moisture content by storage in the laboratory they were weighed. Subsequently the ears were pulled off and weighed. The year 1947 had an excellent

harvest period and sampling was carried out easily and expeditiously. In 1948, however, the weather broke badly during the harvesting period and sampling had to be sporadic, with the result that the later samples suffered irregular losses due to damage by shedding, birds, and mice.

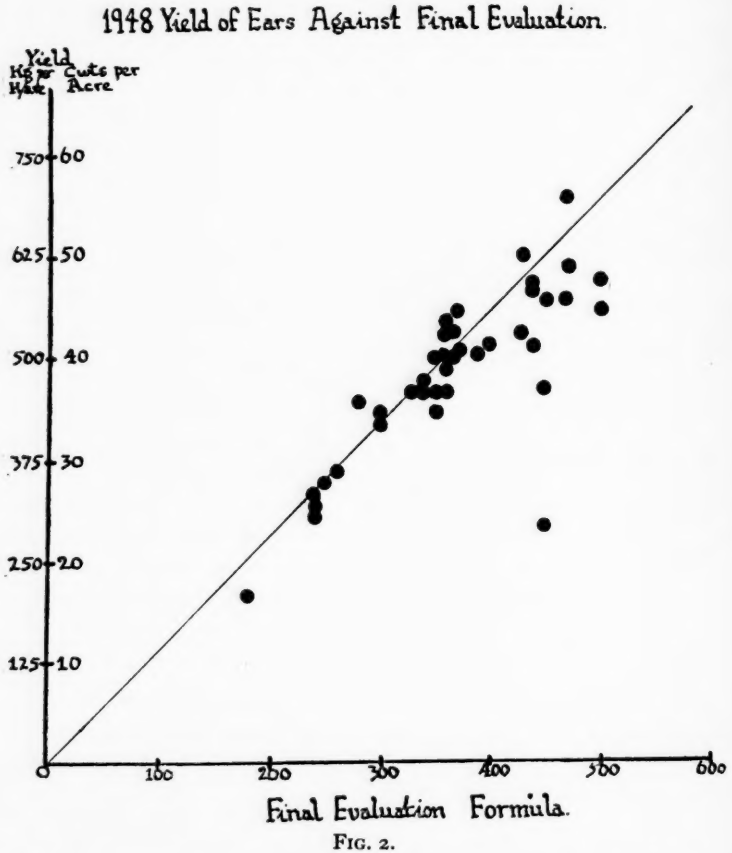

FIG. 2.

Subsequent to the crop-sampling, profile pits were dug in the centre of each quadrat and the profile was recorded and evaluated by the method already described. The yield data and the soil-evaluation figures were then submitted to the Department of Design and Analysis of Scientific Experiment for statistical analysis.

Testing the Validity of the Prediction Formulae

$$P = cVG.$$

The analysis of the data is mainly confined to the prediction of the yield of ears and of straw from the evaluation of the texture and drainage

factors on the one hand and the yield of ears from the evaluation of the texture factor down to the top of the gley horizon on the other.

Figs. 1 and 2 give the dot-diagrams connecting yield of ears for the years 1947 and 1948 with the full evaluation of the profile using the

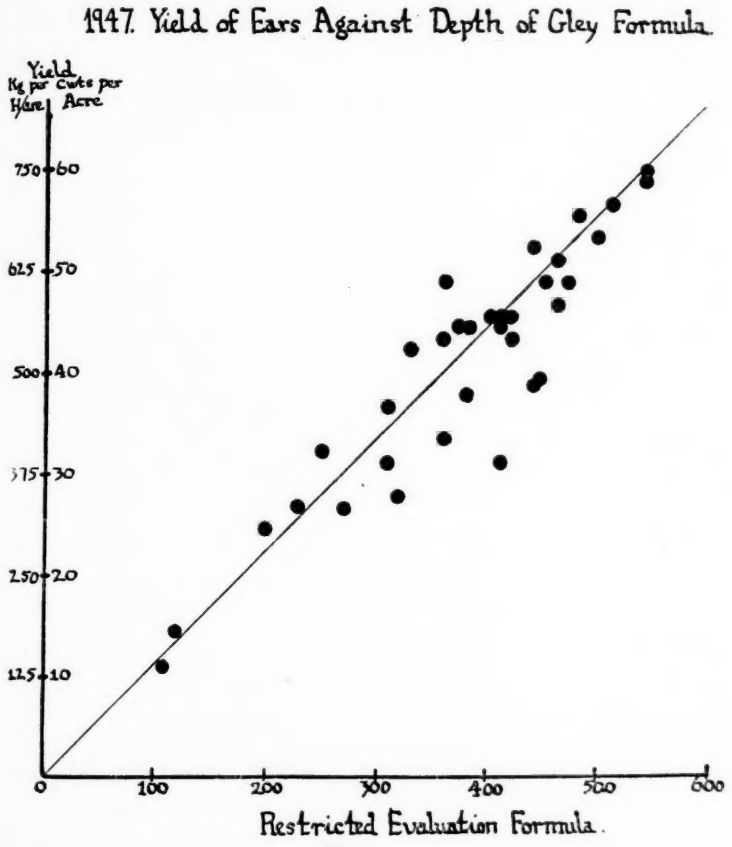

FIG. 3.

drainage factor, whilst Figs. 3 and 4 give the corresponding diagrams using the restricted evaluation down to the gley. In each case the line drawn is the regression line of yield on evaluation determined by the method described below. It can be seen immediately that the points fall very nearly on the regression line in Fig. 1, that the fit is not quite so good in Fig. 3, and it is definitely worse in Figs. 2 and 4, largely because of one point lying well below the line, presumably because much of the grain in this sample was lost before weighing.

The validity of the first prediction formula was tested in the following way. It was assumed that the yield P could be expressed in terms of the

texture value V of the top 30 in. of soil and the drainage factor G by the following formula

$$P = cV^aG^b,$$

where a, b, and c are constants. These constants were fitted by using the regression equation

$$\log P = \log c + a \log V + b \log G,$$

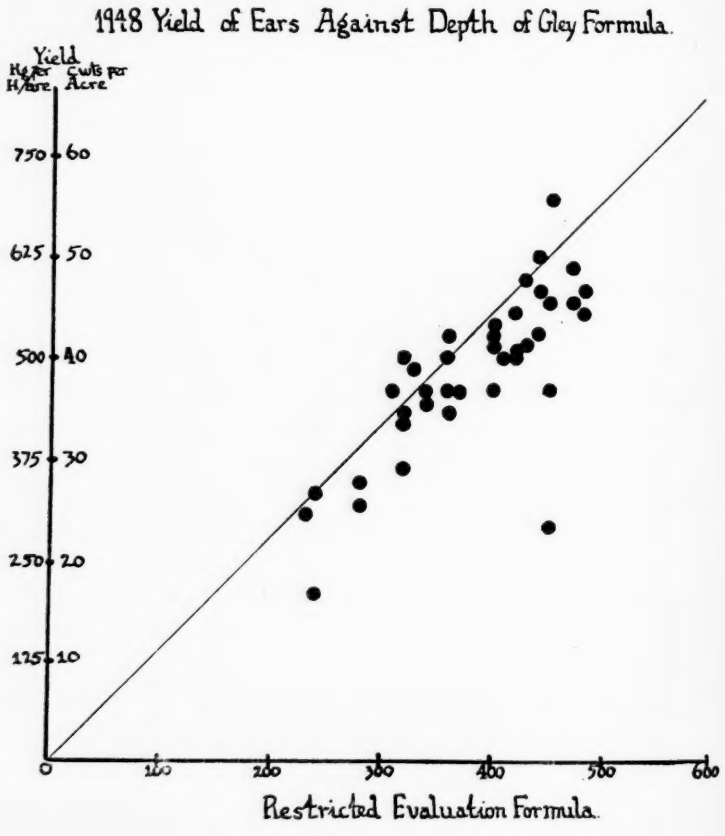

FIG. 4.

and the percentage of the variance of log P that could be accounted for by the regression equation was also computed.

The validity of the second prediction formula was only tested on ear weights, and it was assumed that P could be expressed by the formula

$$P = kV_G^n,$$

where k and n are constants and V_G is the texture value down to the top

of the gley horizon. k and n were then computed for the regression equation

$$\log P = \log k + n \log V_G.$$

The 1947 data

Of the 51 quadrats sampled, 35 were on clay and 16 on limestone soils. It was decided to carry out the analysis for these two types of soil separately. The results were:

Prediction of Ear Weight

	a	b	% *variance of log P accounted for*
Clay soils	1·07±0·09	1·03±0·04	97
	n		
	0·96±0·06		90
Limestone soils	1·05±0·11	1·28±0·34	90

Prediction of Straw Weight

Clay soils	0·10±0·28	0·77±0·13	54
Limestone soils	1·31±0·17	1·59±0·50	86

The prediction of ear weights from the full evaluation is very accurate for the clay soils and very satisfactory for the limestone. The prediction for straw weights is also quite good for the limestone soils, but only poor for the clays, though this is largely due to two of the straw yields being very much lower than expected, for reasons that are not known.

The values of a and b do not differ significantly from unity for the ear weights or for the straw weights on the limestone soils. Further, three out of the four coefficients given for the ear weights are very close to unity whilst the fourth, that of b for the limestone soils, is very inaccurately determined because only 3 out of the 16 soils showed any impedance of drainage. The values of a and b differ much more from unity for the straw weights, but they all have appreciable standard errors and only one differs significantly from unity, namely the value of a for the clay soils. However, as already noted, the regression equation only gives a poor prediction on these soils.

The prediction using the texture value to the depth of the gley horizon has only been worked out for the yield of ears on the clay soils. It is not quite as efficient as the full formula, but again the coefficient n is close to unity.

A further analysis was made to test if the prediction formula could be improved by incorporating a term depending on the depth at which a tough clay subsoil appeared, but the modifications tried effected no improvement in the accuracy of the prediction formula.

The 1948 data

In this year data were collected for 49 quadrats, 8 of which were taken on limestone soils, and this number is not sufficient to justify a statistical

analysis of the data relating to them. The remaining 41 pairs of observations on clay soils were analysed in the same way as in 1947 and the values of the regression coefficients and the goodness of fit of the regression equations were

Prediction for Ear Weights

	a	*b*	*n*	% *variance of log P accounted for*
Clay soils . .	0·94±0·15	0·80±0·15	0·95±0·12	68 / 60

Prediction for Straw Weights

Clay soils . .	0·93±0·18	0·23±0·18	..

As already noted, the prediction formula is much less accurate in 1948 than in 1947, but this is only to be expected because less accurate values for yields had to be used. As a consequence the standard errors of the regression coefficients are much higher for the yield of ears than in 1947, though they are about the same for the yield of straw. The only one of these coefficients that differs significantly from unity again occurs in the straw regression equation, but this year it is the coefficient for the drainage factor whilst in the previous year it was for the texture value. Again, however, the prediction for the straw yield is only poor.

Discussion

The following points have been established in the preceding section. It appears to be possible to arrive at a good prediction for the yield of ears from this evaluation of the soil profile, and the prediction formula for soils on limestone and for clay soils appears to be very similar. Now the full prediction formula is based on obtaining a texture evaluation down to 30 in. in depth and then reducing this according to the depth of the soil or the height of the gley horizon. It seemed reasonable to assume that it might be possible to get as good a prediction on the clay soils by obtaining a texture evaluation down to the top of the gley horizon only, but the results given above do not entirely bear this out. The interpretation of this result is that the wheat roots presumably can make some use of the soil in the gley layer.

Acknowledgements

The author is deeply indebted to Mr. D. J. Finney and Mr. J. M. Hammersley for all the statistical work during the experiments, to Dr. E. W. Russell for all his generous help and advice, and finally to Professor G. E. Blackman who first suggested that this line of approach to soil-profile evaluation should be attempted.

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STUDIES ON SOIL SYSTEMATICS: THE BLACK SOILS OF THE MADRAS DECCAN

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The black soils of the Madras Deccan undoubtedly constitute one of the group of soils commonly known as the black cotton soils of India or the regur soils. Their fertility and distinctive character are almost universally known. But their exact place among the soil types of the world is still, for want of accurately determined facts regarding them, a subject of conjecture.

These soils have been described by Kossovich in *Die Schwarzerde* as black earths which are clayey, heavy, and sticky, being 1–2 metres in depth lying over a loess-like material which itself rests on gneiss or trap. Leaching or eluviation is mainly confined to $CaCO_3$ which accumulates in the lower layers in the form of concretions known locally as *Kankur*. They are formed under the precipitation of an arid climate with less than 1,200 mm. and a high average temperature. Vegetation is largely grass or shrubs and trees are markedly absent. For these reasons these soils were classified as chernozems identical with the black earths of Russia, but are, however, recognized to possess at the same time certain important differences. They do not possess the good structure of the typical chernozem, are difficult to cultivate, relatively poorer in organic matter, and are more like allied formations of the tropics and sub-tropics of the world such as the 'tirs' of Morocco or the 'badob' soils of the Sudan. So little is known about these tropical formations that, at present, it is considered that the resemblances existing among them are determined by identity of climate and conditions of cultivation, and that they can at best be grouped under a tentative type. 'Sigmond (1938) in fact would assign these to a main type of tropical and sub-tropical black soils. It is the object of the present paper to record and examine the notes made of the black soils of the Madras Deccan with a view to determining their place in a general system of soil classification.

Materials and Methods

The materials used are wholly drawn from the report of the soil survey of the Tungabhadra Project Area by P. Venkataramiah, published by the Department of Agriculture, Madras. The Project Area may be described in the words of the author himself as under.

The area proposed to be commanded by the project lies in the taluks of Hospet, Rayadrug, Bellary, Siruguppa, Adoni, and Alur of the Bellary District, Pathikonda and Kurnool in the Kurnool District, and Gooty in the Anantapur District. The

command proposed has a total area of 1,072,500 acres of which 784,000 lie in the Bellary District, 160,300 in the Kurnool District, and the remaining 128,200 in the Anantapur District.

The project area is bounded on the West and North by the Tungabhadra river, between Hospet and Kurnool. The southern boundary is formed by the spurs of the Sandur hills and eastern and south-eastern boundaries are formed by the alignment of the main canal, after its crossing the Hagari river till it reaches Kurnool. There is a small strip south-east of Guntakal, where the command extends to Gooty, between two small ranges of broken hills, reaching down to Pamidi on the Pennar river.

The whole region is by no means homogeneous in its geography, topography, or pedology. The soils are for the most part black, with and without gypsum, the red and mixed soils covering less than a quarter of the total area. The black soils, as will be seen from the sequel, are divisible into two main groups—the deep and the shallow, but have the same characteristics, of being rich in clay with a high moisture holding capacity and high fertility.

The discussion in this paper is based on a close and careful examination of about 400 profile pits spread over an area of approximately one million acres, the pits being located almost at random at 4- to 5-mile distances from one another. Each pit was excavated down to the bed-rock which nowhere exceeded 8 ft. in depth. Detailed systematic notes have been recorded of the location, topography, surface vegetation, and, in addition, particulars of each layer of the profile in respect of colour, structure, presence or absence of carbonates, hardness, &c.

Agriculture of the Area

The soils of the area fall into three groups, (1) black, (2) mixed, and (3) red soils. These are mostly under dry cultivation entirely depending on rainfall. There are, however, irrigated areas both under river channels and under tanks that include all the soil grades. The cropping season varies with the nature of the soil. There are two cropping seasons in this area, viz., '*Mungari*' and '*Hingari*'. Those soils which grow crops during the south-west monsoon period are called the '*Mungari*' areas, and others which grow crops in the post-monsoon period are called '*Hingari*' areas. Red and mixed soils, being less retentive, are usually cropped during the monsoon, and the black soils, having high retentive power for moisture, are sown after the soaking rains at the end of the south-west monsoon.

The main object of Venkataramiah's survey was to determine the effect of bringing these soils under irrigation, and the conclusion arrived at in the published report of the Survey regarding the different kinds of soil in the tract is already briefly given; but no attempt is made therein to fix this soil region into one or other of the recognized systems of soil classes although a great deal of information has been recorded with detailed notes of a morphological and analytical character on which are based the discussion and more important conclusions of this note.

In the first instance, there are within the area surveyed the obvious and broadly distinct occurrences of gypseous and non-gypseous profile development. An analysis of the 407 profiles examined shows 143 are gypseous and 182 are non-gypseous, black soils making up more than 80 per cent. of the area.

A more detailed examination of the features of the gypseous profiles affords interesting information.

It is possible to make out the main morphological features of two different types of formations in the gypsum-containing soils.

	Type I	*Type II*
A.	Black, or mouse-grey, heavy clayey, prismatic, slightly tending to columnar; compact and heavy below second foot; with specks of *Kankur* increasing in size down the profile.	Same as for Type I.
C 1.	Gypsum accumulations.	Calcium carbonate or *Kankur*.
C 2.	*Kankur* in and with white or yellow clay.	Gypsum—crystals.
C 3.	Whitish or yellowish clay resting on granite.	Whitish or yellowish-white clay resting on granite.

The chief difference between the two lies in the disposition of the layer of gypsum relatively to that of the carbonate: in one type above and in the other below. This is indicative of an important difference in the direction of eluviation, as will be seen from the discussion. This difference in general trend of profile formation receives some support from the composition of water extracts of the soils of the two types. The relevant figures are extracted from the data already reported (Table 1).

TABLE 1

Total Salts per cent. in the Soils of the Two Profiles

Soil zone analysed	*Profile pit numbers*												
	Type I						*Type II*						
	1	*41*	*63*	*89*	*228*	*403*	*121*	*125*	*147*	*163*	*193*	*197*	*399*
0–12 in.	0·093	0·095	0·056	0·08	0·064	0·133	0·060	0·065	0·082	0·115	0·105	0·118	0·084
12–24 in.	0·312	0·115	0·70	0·186	0·149	0·950	0·065	0·085	0·105	0·136	0·156	0·262	0·362
24–36 in.	1·670	0·360	0·100	0·820	0·282	2·040	0·095	0·125	0·157	0·230	0·196	0·594	0·161
36–48 in.	1·160	1·630	0·130	1·380	0·304	1·005	0·193	0·899	0·297	0·815	0·231	1·804	2·119
48–60 in.	1·781	0·819	0·738	0·600	0·525	0·505	0·284	1·532	0·553	1·912	0·288	0·283	..
Average salt content of the top 3 ft. zone					0·042					0·016			
Average salt content (total solids) of the zone below the above . . .					0·881					0·95			

It will be seen that there is generally a higher concentration of soluble salts in soils of type I nearer to the surface than in soils of type II. This may be due either to defective leaching under conditions of greater aridity or to rise of salts from below due to regrading.

In their distribution within the area surveyed, the two types occur over fairly well-defined and compact areas with significant variations in local agricultural practices. Thus type I (gypsum accumulations nearer the surface) is met with in areas where tank irrigation is rarely the practice, while type II is found in areas where tank irrigation is more popular. These features, viz. compactness, contiguity, and irrigability, indicate that the two types are not fortuitous soil occurrences but may have arisen as a result of some local differences in the influence of soil-forming factors.

Discussion

The black cotton or regur soils of India have no doubt much in common with the chernozem, but are formed under a more tropical climate with about the same total precipitation and with alternating wet and dry periods. A typical chernozem has really no illuviation zone at all. Its A horizon is dark with high amounts of mild humus. The occurrence of gypsum is rare, and the only type of illuviation is of calcium-carbonate deposition. The main direction of illuviation is on the whole invariably downward, as indicated by the existence of krotovines filled with calcium carbonate.

The invariable occurrence of gypsum in the black cotton soils of India is definitely indicative of a more restricted action of water during the 'building up' of the profile. They therefore resemble in this respect the soils of a more arid zone than that of the chernozem, making possible the accumulation of gypsum and alkali salts in the soil zone itself. The general soil-forming process is, however, exactly that of the typical chernozem area, the overall chemical action proceeding no farther than the mobilization and movement of alkali and alkaline-earth bases. The typical chernozem character is thus greatly reduced in intensity, as is found in the brown or grey steppe groups of soils of Russia. These soils, according to 'Sigmond, are formed like the chernozem on loess-like material but with a precipitation of less than 1,000 mm. as against the 1,200 mm. of the chernozem zone.

For these reasons the regur soils should be considered to be different from the chernozem proper and to be like either the chernozem of the Hungarian lowlands or the brown steppe soils of Russia. The dynamic characteristics of the latter soil types are given by 'Sigmond as below.

> Leaching is restricted chiefly to alkali salts, the $CaCO_3$ and gypsum being less intensively leached. A characteristic feature is that the gypsum horizon lies deeper than the $CaCO_3$ concretion and the leaching is mainly downward. The sesquioxides and silica are stable as in the typical chernozem and other calcium soils. The amount of humus is much less, being less than 4 per cent. in all the horizons.

The resemblance between these and one of the two groups of our regur (i.e. type II) soils is very close indeed and it is best classified as belonging to the type of soils called 'brown steppe'.

The other type met with in the Deccan area is essentially different, since the disposition of the gypsum accumulation above the carbonate concretion is definite evidence of upward eluviation and, in consequence, of an altogether different type of formation. This difference in the direction of profile building may have taken place as a primary pro-arid type following on a change in the general direction of eluviation in the region affected or as a secondary process somewhat allied to what takes place in regraded alkali soils or in the leached alkali soil types. It will be seen that the main point of difference between the two soil classes lies in the relative altered positions of calcium-carbonate and calcium-sulphate accumulations. Among the various natural factors contributory to a difference of the above kind, the general climate of the place and nature

of topography are the most potent; for these alone influence or modify the general direction of profile formation resulting in an ABC or ACB type of profile, in addition to its intensity. In the particular instance, for example, the rainfall and average temperature of the places being characteristic of an arid climate, the alkalis and alkaline-earth bases will move on the whole either downward or upward depending on the extent of aridity and the presence or otherwise of impervious layers of the regolith tending to impede movement; the former being the cause of excessive evaporation from the surface of the soils and the latter causing, by its impedance to the downward movement of water, a rise of the local water-table and bringing it near to the soil surface and thus reversing the direction of water movement in the long run. The entire area surveyed enjoys an annual rainfall of about 22 in. and an average temperature of 80° F. which is fairly uniform over the whole area. The general topography is undulating over the regions of either type of soil, the average altitudes being about 1,500 ft. above mean sea-level.

It is, however, possible that, while the topography of the place reveals nothing distinctive, the impervious parent rocks may present localized folded surfaces to downward-moving streams of water and thus bring about the formation of what are known as perched water-tables. If such a feature had obtained at some early stage of profile formation over certain portions of the tract and not in others, the occurrence in closely contiguous areas of two different soils such as types I and II is easy to understand.

Whatever may be the exact nature of the causes at work, the existence of two different types of soils is clear, and it is interesting to speculate on their probable reaction to irrigation agriculture. There can be little doubt that the brown steppe soils of the area (i.e. type II) will be little affected by the introduction of a more humid system of agriculture, such as irrigation, which will merely emphasize its natural trends, and provided lime status is maintained the agricultural properties of the region will change little under irrigation.

It is doubtful, however, whether type I will respond similarly to irrigation. Whatever may be the reason for the differences noticed, increased supply of water at the surface may bring about either the restoration of the typical and more humid chernozem process in soils of the brown steppe group or accentuate the alkalization of the upper horizon in the leached alkali soils. The latter result may have very undesirable effects on the agricultural properties of these soils. In this connexion it is significant that the practice obtains in the Madras Deccan of utilizing natural irrigation sources such as tanks only in areas where the soils are of the brown steppe type and not in areas where the soils are of the leached alkali type and show a tendency under irrigation to become more and more alkaline. The lack of popularity of irrigation in these soils is perhaps due to this cause.

Conclusion

The black cotton soils of the Madras Deccan present the major characteristics of the European chernozem, but differ from it in important

characteristics. They are more like the formations of drier regions such as the steppe soils of the Hungarian lowlands.

Two modifications of the general chernozem process appear to have dominated the soil-forming processes in the area, resulting in types allied to the brown steppe soils and leached alkali soils.

The reasons for the existence of these modifications is at present not known. Their significance to irrigation agriculture is pointed out.

REFERENCE

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A REVIEW OF RECENT WORK ON SOIL ORGANIC MATTER
PART I

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ALTHOUGH no great progress has been made in the study of soil organic matter since Waksman's comprehensive review of the subject in 1938 (1), much useful information has been obtained and several points have been clarified. Since the literature published during this period is too extensive for adequate treatment here, this article will deal with only a few of the important developments in the field. Progress in other directions will be reviewed later.

The Uronic Fraction of Soil Organic Matter

Uronic acids are commonly determined by the method of Lefèvre and Tollens (2) which depends upon the fact that uronic acids are quantitatively decarboxylated when boiled with 12 per cent. hydrochloric acid. This method has been applied to soils by various workers (3–13) and the results have been taken to indicate that a considerable fraction of soil organic matter is in the form of uronide material. Shorey and Martin (3), who first used the method for soil analysis, found that from 12·8 to 28·4 per cent. of the organic carbon in nine soils examined could be accounted for as uronic carbon. Results obtained by Norman and Bartholomew (7) in a study of the distribution of apparent uronic carbon in 20 soil profiles indicated that about 10–15 per cent. of the organic carbon of surface soils is in the form of uronides. The proportion was found to increase with depth, particularly in podzolized soils, in which a marked accumulation was found in the B horizon. The apparent uronic carbon in the B_2 sample of a sandy loam represented 38 per cent. of the total carbon. Fuller (10) found that about 9–23 per cent. of the organic carbon in surface soils and 19–30 per cent. of that in subsoils appeared to be uronic. Data obtained by Fuller, Bartholomew, and Norman (9) on samples of a single soil type indicated that in spite of wide variations in clay content and organic carbon the proportion of uronic carbon to total carbon remained rather constant. Fuller (11) determined the apparent uronic carbon in the surface soils of 9 soil types that had been planted continuously to a single crop for 25 or more years or to a stable crop rotation and found that the proportion of uronic to total carbon in a single soil type changed only slightly as a result of different cropping and fertilizer treatments. The changes appeared to be more closely related to the total carbon content than to the nature of the crop or cropping system; the lower the total carbon content of a given soil, the higher the percentage of uronic carbon in the organic matter, regardless of the crop. As much as 30–40 per cent. of the total carbon in several of the soils appeared to be uronic.

Although the term 'apparent uronic carbon' has been used in the

presentation of results obtained by the Lefèvre–Tollens method, it has nevertheless been assumed that the carbon dioxide obtained from soils on boiling with 12 per cent. hydrochloric acid is derived from uronic groups. Support for this assumption was provided by the fact that no carboxyl groups other than uronic were known to yield more than small quantities of carbon dioxide under the conditions of the determination (9). Sugars, polysaccharides, and other substances tested were found to evolve small quantities of carbon dioxide, but quantitative significance could not be attached to the carbon dioxide liberated from these sources (14, 15, 16). Moreover, it was found that soils contained no substances which interfered with the determination of the uronic groups in pectin (7, 8, 9, 13). Further support came from the finding that the rate of carbon-dioxide evolution from soils was similar to the rate of decarboxylation of uronic units in plant gums, plant materials, and bacterial gums (8, 10), and that changes in temperature and acid concentration influenced very similarly the rate of carbon-dioxide evolution from pectin and from soils (9). Fuller (8, 10) found that the rate of carbon-dioxide evolution from soils more closely resembled the rate from bacterial than from plant uronides and took this as evidence of the microbiological origin of soil uronides.

The reviewer considers that the presumptive evidence presented above does not justify the assumption that the carbon dioxide evolved on boiling soils with 12 per cent. hydrochloric acid is derived from uronic groups. It is hardly credible that such a large proportion of soil organic matter should be in the form of uronides. It is even more difficult to understand why the proportion should increase with depth. It must be remembered that, if the method is specific, it is only the uronic grouping that is determined by the Lefèvre–Tollens procedure. Since the exclusive presence of pure polyuronides in soil is most improbable, the amount of uronide-containing polysaccharides would be considerably greater than uronic-carbon figures at first indicate. Some calculations based on results recently published (13) will help to make this clear. A red laterite soil containing 4·75 per cent. organic carbon was found by the Lefèvre–Tollens method to have a uronic-anhydride content of 6·16 per cent. The apparent uronic carbon therefore constituted 53 per cent. of the total soil carbon. Assuming that soil organic matter contains about 58 per cent. carbon, this means that even if the uronic carbon were in the form of *pure* polyuronides, the latter would account for about 75 per cent. of the soil organic matter. On the much more reasonable assumption that the uronic carbon occurs in the form of a polysaccharide of high uronic content such as pectin (48·4 per cent. uronic anhydride), the uronic complexes would account for some 155 per cent. of the soil organic matter. The absurdity of this result forces the conclusion that whatever the origin of the carbon dioxide evolved on boiling soils with 12 per cent. hydrochloric acid, it is not all derived from uronic acids. Mattson and Koutler-Andersson (17) reached a similar conclusion in 1944, but their work appears to have been overlooked. They found very little hydrolysable acidoids and practically no hydrolytic activity in humus and deduced that the presence of large amounts of uronic-acid

complexes was very improbable. They also found that the uronic-anhydride content of beech lignin, as determined by the Lefèvre–Tollens method, increased from 2·3 to 10·1 per cent. as a result of autoxidation. As Mattson and Koutler-Andersson have pointed out, the lignin complex can hardly be expected to form uronic acids by autoxidation. On the basis of this observation, which would repay more detailed investigation, it would appear likely that a significant fraction of the carbon dioxide obtained on boiling soils with 12 per cent. hydrochloric acid is derived from the oxidized lignin complexes which are believed to contribute substantially to soil organic matter. A study of the rates of decarboxylation of autoxidized lignin preparations may prove illuminating.

It is obvious that the necessity of decarboxylating the apparent uronic constituents of soil in the presence of large amounts of extraneous material presents a real opportunity for non-uronic constituents to interfere. Little is known of the chemistry of soil organic matter and it is quite likely that some substance or substances present in soil and not previously tested may interfere seriously with the determination of uronic acids. In this respect attention may be drawn to the recent work of Tracey (18), who found that a number of substances not previously tested gave considerable yields of carbon dioxide when boiled with 12 per cent. hydrochloric acid. Some of these substances have been isolated from soils in traces.

The uronic content of mature plant materials is generally low, most of the uronic groups forming part of the encrusting polyuronide hemicelluloses. Studies on the biological decomposition of plant materials have shown that the uronic complexes appear to be less rapidly decomposed than cellulose or the pentose groupings of the hemicelluloses (4) and that the apparent uronic content of decomposed residues is frequently no lower than that of the parent plant material (10, 19). No satisfactory explanation of these results or of the apparent resistance and accumulation of uronides in soils has yet been advanced. The possibilities have been offered that the uronide groups in plant hemicelluloses are, as such, highly resistant to decomposition (4) or that the decomposition of plant materials is accompanied by microbial synthesis of uronides that are not readily utilized (7, 10). It is difficult to entertain either of these possibilities since pure polyuronides such as pectin and alginic acid are rapidly attacked by a wide range of micro-organisms and there is no evidence to suggest that the uronic groups in plant hemicelluloses or in microbial polysaccharides are less susceptible to attack. Another possibility advanced is that the uronic complexes, whether of plant or microbial origin, are stabilized by association or combination with some other organic or inorganic complex (4, 7, 10, 20). As shown below, a similar explanation has been brought forward to account for the stability of soil organic nitrogen. The possibility that uronic complexes are stabilized in this way cannot be ignored, but as yet there is no evidence to support this theory. Fuller (12) reasoned that if the uronic constituents of soil are not associated with other organic constituents their separation from soil should not be difficult. He found, however, that the uronic and non-uronic organic constituents of soil were extracted in about equal

proportions by various reagents known to extract plant polyuronides. This was taken to indicate that these constituents may be combined. It is not really surprising, however, that separation of uronides from other organic complexes was not achieved in this work since the reagents employed are known to extract other fractions of soil organic matter. Moreover, no attempt was made to fractionate the extracts.

Although Shorey and Martin (3) reported the separation from soils of colloidal materials having some of the properties of uronide complexes, the only real direct evidence for the presence of uronic acids in soils is that recently obtained by Forsyth, who isolated polysaccharides containing uronic groups from the fulvic fractions of soil extracts by means of a selective-adsorption technique (21). Ash-free polysaccharide complexes obtained from a wide range of soils by this technique were found to have very similar properties (22). They contained the same sugars, namely, galactose, glucose, mannose, arabinose, xylose, and glucuronic acid, but the proportions of the various sugars, especially of the pentoses, varied to some extent in the different preparations. Like polysaccharides synthesized by soil bacteria they contained small amounts of nitrogen and ribose, suggesting that they were microbial products. The polysaccharide complex from one soil was studied in greater detail, the constituent sugars being determined by paper chromatography and by specific precipitants. The results agreed well with a repeating unit containing galactose (2 mol.); glucose (2 mol.); mannose (2 mol.); arabinose (1 mol.); xylose (3 mol.); 2 mol. of aldobionic acid consisting of glucose and glucuronic acid. The preparation contained 15·8 per cent. uronic anhydride and had a titration equivalent of 1,185. The amount of polysaccharide isolated from this soil represented about 1 per cent. of the total soil organic matter. The apparent uronic carbon in the soil was unfortunately not determined, but assuming that it constituted about 10 per cent. of the total soil carbon—a very conservative estimate—and that soil organic matter contains about 58 per cent. carbon, then only 1·3 per cent. of the apparent uronic carbon in the soil was isolated in the form of polysaccharide. Although this does not detract from the value of Forsyth's excellent work it does place his results in their proper perspective with regard to apparent uronic-carbon figures, and emphasizes the fact that as yet there is no direct evidence to justify faith in figures obtained by application of the Lefèvre–Tollens procedure to soils. Final judgment on the value of this method in soil analysis must be postponed until uronides have been isolated from soils in quantities sufficient to account for the observed yields of carbon dioxide.

The Organic Phosphorus of Soils

Studies on the nature and behaviour of soil organic phosphorus have proved to be rather difficult because of the complexity of the material and because the amount present in soil is generally very small. The inorganic fraction of soil phosphorus has received much greater attention. Recent literature on soil phosphorus, however, reflects a growing interest in the organic fraction and a greater appreciation of its importance.

Distribution of organic phosphorus in soils

Two methods have been employed for the determination of organic phosphorus in soils. Both are indirect procedures. In one the increase in acid-soluble phosphorus following oxidation of the soil organic matter with hydrogen peroxide is determined (23, 24). In the other, which is probably more reliable, the soil is first leached with acid and the organic phosphorus then extracted with alkali and determined from the total and inorganic phosphorus contents of the extract (25–36). Both methods are open to criticism, but their application to soils has established beyond reasonable doubt that a large fraction of soil phosphorus is in organic combination. Pearson and Simonson (31), for example, found that from 27·2 to 72·6 per cent. of the total phosphorus in the surface layers of seven Iowa soil profiles was organic. Results obtained by Kaila (34) from analyses of 100 Finnish soils showed that in mineral soils about 40 per cent., and in peat soils about 60 per cent., of the phosphorus was in organic form. The proportion of phosphorus in organic combination has been found to decrease with depth in the profile, as would be expected from the decrease in organic matter (26, 27, 31, 35, 37). Wide variations in the ratios of organic phosphorus to organic carbon or nitrogen in different soils have been reported (24, 26, 28, 30, 31, 34, 35, 36, 38). Pearson and Simonson (31) found that the ratios varied within individual profiles as well as from soil to soil and that smaller variations occurred in the nitrogen-phosphorus ratio than in the carbon-phosphorus ratio. Kaila (34), on the other hand, found that the proportion of organic phosphorus depended mainly on the organic carbon content of the soil. The ratio of organic carbon to organic phosphorus in 70 mineral soils examined was found to be roughly constant, ranging from about 100 to 150. The ratio of organic nitrogen to organic phosphorus in the same soils varied from 4 to 18, the average being about 8·4.

It may be pointed out here that the organic phosphorus complexes of soil are more readily extracted than other fractions of soil organic matter. The acid-alkali extraction procedure used for the determination of total organic phosphorus generally dissolves only about 50–60 per cent. of the organic carbon.

Chemical nature of soil organic phosphorus

The approach followed in studies on the chemical nature of soil organic phosphorus has been to examine soils for the types of organic phosphorus compounds known to be present in plants and micro-organisms. Attention has therefore been focused on nucleic acids, which are the principal organic phosphorus compounds of both plants and micro-organisms, and on phytin, which occurs in significant amounts in most plants, especially in the seeds. A search has also been made for phospholipids, which are essential constituents of cells.

Phospholipids. Several workers have shown that soils contain organic phosphorus compounds which, like phospholipids, are soluble in ether (29, 39, 40, 41, 42). This has been taken as evidence for the presence of phospholipids in soil organic matter, and the phospholipid-phosphorus

contents of various soils have been estimated from the amounts of ether-soluble phosphorus. The results indicate that only trace amounts of phospholipid-phosphorus occur in soils. Wrenshall and McKibbin (29), for example, found that only about 0·3 per cent. of the organic phosphorus in two soils examined was ether-soluble.

Nucleic acids. Evidence for the presence of nucleic acids in soil organic matter has been obtained by the detection of their hydrolysis products, namely, phosphoric acid, pentose sugars, and purine and pyrimidine bases, in the hydrolysates of phosphorus-rich fractions of soil organic matter (29, 43, 44, 45). Further evidence has been provided by the isolation from soils of compounds such as xanthine and hypoxanthine, which are formed by microbial decomposition of nucleic acids (46, 47). These findings, taken with those of Bower (51), which are discussed below, indicate that nucleic acids or nucleotides occur in soil. However, no definite information regarding the proportion of soil organic phosphorus in the form of nucleic acids is yet available. Methods recently devised for the quantitative determination of nucleic-acid constituents should prove helpful in obtaining such information.

Phytin and its derivatives. Phytin, in the strict sense of the word, is the calcium-magnesium salt of inositol hexaphosphoric acid (phytic acid). The use of the term has been broadened, however, to include any inositol hexaphosphate, and compounds such as inositol triphosphate and inositol monophosphate, which are formed by partial dephosphorylation of phytin by the enzyme phytase, are commonly referred to as phytin derivatives.

Recent work has definitely established the presence of various inositol phosphates in soils. Yoshida (48) obtained preparations rich in organic phosphorus by fractionation of alkali extracts of three Hawaiian soils and found that they yielded inositol and phosphoric acid upon acid hydrolysis. The phosphorus and ammonia-nitrogen contents of one of the preparations suggested the presence of the ammonium salt of inositol monophosphate. No evidence for the presence of nucleic acids in the preparations could be obtained. Wrenshall and his co-workers (45, 49) obtained an organic phosphorus preparation from an alkali extract of a Quebec podzol soil by a procedure which involved bromination of the extract followed by acidification and addition of ferric chloride. The precipitate thus obtained was free of nitrogen and contained phosphorus and iron in a ratio corresponding with that of ferric phytate. The sodium salt of the preparation gave the Fischler and Kurten test for phytin and resembled authentic sodium phytate in its behaviour towards dephosphorylating enzymes. It was concluded that the organic phosphorus in the preparation was in the form of phytin. Bower (50) obtained organic phosphorus preparations from three Iowa soils by a similar procedure and found that part of the organic phosphorus in the filtrates from the iron precipitates was precipitated by calcium under alkaline conditions. Determinations of the inositol : phosphorus ratios of the iron precipitates showed that their organic phosphorus was in the form of phytin. Similar determinations on the calcium precipitates indicated that their organic phosphorus was in the form of phytin derivatives, the inositol : phos-

phorus ratios corresponding most closely to that of inositol triphosphate. Inositol monophosphate could not be detected in any of the soils studied. The results obtained indicated that two of the soils contained about 35 per cent. of their total organic phosphorus in the form of phytin and 12 per cent. in the form of phytin derivatives. The corresponding figures for the other soil were 27 and 14 per cent. Between 40 and 50 per cent. of the total organic phosphorus in the three soils examined was thus accounted for as phytin and its derivatives. Bower (51) later found that phytin and its derivatives, with the exception of the monophosphate, could be separated quantitatively from nucleic acid by precipitating the former as calcium salts under alkaline conditions. When this method of fractionation was applied to alkali extracts of three soils the major part (67–83 per cent.) of the organic phosphorus present behaved like phytin and its derivatives in that it was precipitated by calcium, and the remainder behaved like nucleic acid in that it remained soluble. Dephosphorylation studies using alkaline sodium hypobromite and enzymes from corn roots and wheat bran showed that the two fractions behaved like phytin and nucleic acid, respectively.

The work described above has led to the view that most of the organic phosphorus of soils is in the form of phytin, nucleic acids, and their decomposition products. The contention that a considerable fraction of soil organic phosphorus is in the form of inositol phosphates would appear to be well substantiated. As yet, however, there is no evidence to support a similar contention with regard to nucleic acids.

Availability studies

The belief that soil organic phosphorus is largely in the form of phytin and nucleic acids has naturally led to studies on the availability of these compounds to plants. Several investigators have shown that in culture solution phytin, nucleic acids, and nucleotides are readily utilized by plants (52, 53). Phytin is absorbed directly by some plants (52, 53), whereas nucleic acids are so rapidly dephosphorylated by enzymes occurring in plant roots that it has not been decided whether their phosphorus is absorbed in the organic or inorganic form (52). The conditions of culture-solution studies are very different, however, from those which hold in soils, and most studies have therefore been concerned with the availability of phytin and nucleic acids when added to soils.

Nucleic acids. Several investigators have shown that phosphorus added to soils in the form of nucleic acids is readily utilized by plants (54, 55, 56). Some experiments indicate that it is almost as readily available as phosphorus added in the form of soluble inorganic phosphates (54, 55). Information regarding the availability of nucleic-acid phosphorus has also been obtained by studying the rate and extent of its mineralization when added to soils. Investigations of this nature have shown that the major part of phosphorus added to soils in the form of nucleic acids and nucleotides is rapidly mineralized, presumably by nuclease enzymes (57), but complete mineralization has not been demonstrated. Pearson, Norman, and Chung Ho (58) found that 60–85 per cent. of phosphorus added to a sandy loam in the form of yeast nucleic acid and its

constituent nucleotides was mineralized after 60 days. Dyer and Wrenshall (59) obtained similar results on incubation of these materials with a slightly calcareous soil, but found that whereas ribonucleic acid released about 68 per cent. of its phosphorus as inorganic phosphate when incubated with this soil for 3 weeks, it released only about 10 per cent. when incubated with an acid podzol for the same period. Bower (51) found that the rate of dephosphorylation of added nucleic acid was lower in strongly acid soils than in soils having a pH value of 5·5 or higher. The maximum dephosphorylation observed after incubation of nucleic acid with various soils for 30 days was 77 per cent.

Pearson *et al.* (58) suggested that the incomplete mineralization of nucleic-acid phosphorus added to soils is due to immobilization of part of the phosphorus by the microbial population which develops at the expense of the nucleic-acid carbon. Bower (51) recently suggested that it may also be partly due to the adsorption of nucleic acids by clays, since he found that dephosphorylation of nucleic-acid materials by nuclease enzymes was markedly reduced in the presence of clay minerals. For example, dephosphorylation of yeast nucleoprotein by wheat bran enzymes in a 4-day period was reduced from 42 to 3 per cent. by the presence of bentonite. Tests showed that the effect of clays on dephosphorylation was not due to adsorption and inactivation of the enzymes. The ability of bentonite to stabilize nucleic-acid materials against dephosphorylation was found to be greater than that of kaolinite. These results led Bower to suggest that interactions between nucleic acids and clay minerals in soil may stabilize the former against decomposition and permit their accumulation.

Phytin and its derivatives. Neubauer (54) found that phytin phosphorus was not taken up by rye from soil plus sand culture although it was quite available to the same plant in pure sand culture. Bertramson and Stephenson (55) found that it was not utilized to any appreciable extent by tomatoes grown in acid soils. Conrad (56) found that although phosphorus added as phytin to a neutral soil was as available to milo as an equivalent amount of phosphorus added as monocalcium phosphate, it was practically unavailable in a soil of pH 5·8.

Wrenshall and Dyer (45) pointed out that phytic acid forms insoluble salts with iron and aluminium and showed that such salts were highly resistant to dephosphorylation by phytase in slightly acid medium. They suggested that in acid soils phytic acid is combined with iron and aluminium and is consequently resistant to dephosphorylation and unavailable to plants. The same workers studied the rate of mineralization of phytin phosphorus added to soils and showed that decomposition of phytin in soil was very slow compared with that of nucleic acid (59). In an 8-week period the apparent mineralization of added phytin phosphorus in a slightly calcareous soil was about 50 per cent., whereas in an acid podzol it was only about 5 per cent. Pearson *et al.* (58) also found that the decomposition of phytin added to soil was much slower than that of nucleic acid, and noted that dephosphorylation of phytin in a slightly acid soil was greatly accelerated by the addition of lime, whereas that of nucleic acid was only slightly affected. They suggested that if

most of the phytin in acid soils is in the form of insoluble iron and aluminium phytates, the more rapid decomposition of phytin in the limed soil is due to the greater solubility and, therefore, increased availability to micro-organisms of calcium phytate.

According to Mattson and Koutler-Andersson (60), phytin is fixed in soil by combination with aluminium and iron hydrogels at low pH and with calcium ions at high pH. Kaila (34) studied the biological decomposition of wheat bran in the presence of various cations in the form of nitrates and found that both calcium and aluminium ions retarded mineralization of the phytin present, aluminium being particularly effective.

The presence in soils of inositol phosphates which are formed by partial dephosphorylation of phytin seems well established. Yoshida (48) argues that phytin in plant materials added to soils is probably converted to intermediate inositol phosphates before sufficient iron to fix it is available. Bower (50) considers that the decomposition of phytin in soil is not very rapid since the amounts of phytin phosphorus in soils appear to be much greater than the amounts of phosphorus in the form of phytin derivatives.

It may be pointed out here that phytin has not been identified as a constituent of micro-organisms. This implies that the inositol phosphates present in soil are of plant origin.

Bower (51) pointed out that phytin derivatives, such as inositol triphosphate, do not form insoluble ferric iron and aluminium salts, and that the availability of their phosphorus might therefore be expected to be greater than that of phytin phosphorus. He studied the availability to oats of phosphorus added as phytin and its derivatives to several Iowa soils having a wide range in pH value and found that it was lower in strongly acid than in neutral or slightly alkaline soils. The coefficient of correlation between percentage base saturation of the soils and recovery of phytin phosphorus by the oats was +0·95. Recovery of added phosphorus was very low in acid soils but was quite substantial in one slightly alkaline soil (pH 7·4). In this soil the recovery of added phosphorus was 9·2, 24·4, and 29·8 per cent. for equivalent amounts of phosphorus added as phytin, phytin derivatives, and monocalcium phosphate, respectively. Bower also found that fixation of added phytin, as measured by solubility in weak acid, was greater in strongly acid than in neutral or slightly alkaline soils, and showed that there was an inverse relation between the amount of phytin fixed and the recovery of phytin phosphorus by oats. On an average the soils fixed 92·4, 74·9, and 15·6 per cent. of phosphorus added to them in the form of phytin, phytin derivatives, and monocalcium phosphate, respectively. Bower suggested that the fixation and unavailability of phytin derivatives in acid soils is due to their adsorption by iron and aluminium compounds. He also pointed out that the liming of acid soils should favour the utilization of phytin phosphorus by crops. The results of Pearson *et al.*, discussed above, lead to a similar conclusion. In this respect it may be pointed out that Kaila (34) has recently shown that mineralization of soil organic phosphorus is accelerated by liming.

Taken together, these results suggest that the reactions of phytin in soils are analogous to those of inorganic phosphates. The fixation and availability of both appear to depend chiefly upon the base status of the soil. The indications are that when either inositol phosphates or soluble inorganic phosphates are added to soils highly saturated with bases they combine largely with calcium and magnesium, whereas if added to acid soils they enter into combinations with iron and aluminium. They are less soluble and consequently less available in the latter form.

The conclusion drawn from these studies is that the phosphorus of nucleic acids is more available than the phosphorus of phytin and its derivatives, except possibly in very slightly acid or neutral soils where the availability of phytin and especially of its derivatives may be appreciable.

Although considerable information has thus been obtained regarding the availability of organic phosphorus when added to soils in various forms, little is known about the availability of native soil organic phosphorus. Evidence that the latter is utilized by plants to as great an extent as is the inorganic soil phosphorus has been provided, however, by studies on the changes in the total and organic phosphorus contents of soils upon cultivation. Schollenberger (27) determined the total and organic phosphorus contents of 12 virgin and adjacent cultivated Ohio soils and found that the average percentage loss of total phosphorus upon cultivation was about the same as that of organic phosphorus. Garman (36) reached the same conclusion from analyses of 30 virgin and adjacent cultivated Oklahoma soils. From a study of 8 cropped and comparable virgin Iowa soils, Pearson (61) found that the average loss of organic phosphorus on cultivation was 83 p.p.m., whereas the average loss of inorganic phosphorus was only 55 p.p.m. Considering the fact that soils receive continual additions of organic phosphorus in the form of plant, animal, and microbial residues, these results suggest that the availability of the organic phosphorus of soils is actually greater than that of the inorganic phosphorus.

More recent work has provided information regarding the availability of soil organic phosphorus over short periods of time. Bower (51) studied the mineralization of organic phosphorus in 10 pairs of soil samples from virgin and adjacent cultivated areas by determining both the increase in acid-soluble phosphorus and the decrease in organic phosphorus upon incubation. He found that the average mineralization of organic phosphorus during a month's incubation at 35° C. was 39 p.p.m. in the virgin soils and 11 p.p.m. in the cultivated soils. Thompson (62) obtained similar results. Although these incubation experiments were conducted at a relatively high temperature, which favours the mineralization of soil organic phosphorus (51, 63), this does not detract greatly from the significance of the results. The release of only a few p.p.m. of phosphorus during the growing season would supply a significant proportion of the phosphorus needed for crop production.

It is obvious from the results of these availability studies that the organic fraction of soil phosphorus has not received the attention that it

deserves. It should repay more detailed investigation, both with regard to its nature and its role in the phosphorus cycle.

The Organic Nitrogen of Soils

Considering the importance of nitrogen from the standpoint of soil fertility and the fact that about 98 per cent. of the nitrogen in most soils is organic, the nitrogenous organic complexes of soil have received surprisingly little attention. Very little definite information has been obtained regarding either their nature or their transformations in soil.

Chemical nature of soil organic nitrogen

It has long been assumed that a considerable fraction of soil organic nitrogen is in the form of proteins, but until recently there was no real evidence to support this assumption. Prima-facie evidence has now been obtained by using the highly specific ninhydrin method of Van Slyke, Dillon, MacFadyen, and Hamilton (64) to determine the amino-acid contents of soil hydrolysates. By this method Kojima (65) found that about 37 per cent. of the nitrogen in a highly organic muck soil was liberated as α-amino-nitrogen by acid hydrolysis, and Bremner (66), using six different soils, found 24–37 per cent. Similar amounts of α-amino-nitrogen were found to be released by alkali hydrolysis. These results establish the protein nature of about one-third of the organic nitrogen of soil. This estimate must be regarded as minimal since destruction of amino-acids undoubtedly takes place during hydrolysis. Moreover, soil hydrolysates contain large quantities of ammonia and some of this is probably derived from the acid-amide (asparagine and glutamine) residues of protein material. If it were assumed that all of the ammonia found in soil hydrolysates is derived from such residues, it could be deduced from α-amino-nitrogen and ammonia-nitrogen determinations that as much as 50 per cent. of soil nitrogen is in the form of protein.

Proteins as such have not yet been isolated from soils. The indications are that they are firmly attached to other fractions of soil organic matter.

The amino-acid composition of the protein material in soil has been relatively little studied owing to practical limitations. These limitations have been largely overcome by the introduction of paper partition chromatography, and Bremner (67, 68) has recently studied the amino-acid composition of acid hydrolysates of 10 different soils by this technique. The following 20 amino-acids were found in every hydrolysate examined: phenylalanine, leucine, isoleucine, valine, alanine, glycine, serine, threonine, aspartic acid, glutamic acid, arginine, histidine, lysine, proline, hydroxyproline, α-amino-*n*-butyric acid, β-alanine, γ-amino-butyric acid, αε-diaminopimelic acid, and tyrosine. Methionine sulphoxide and glucosamine were found in most of the hydrolysates, but cystine, methionine, and tryptophan could not be detected. The results indicated that the protein materials in the different soils studied were similar in their amino-acid composition. No free amino-acids could be detected in the soils.

Kojima (69) isolated several amino-acids in good yield from hydrolysates of the muck soil used in her previous work.

The detection of glucosamine in soil hydrolysates confirms previous evidence (66) that 2-amino sugars occur in soil, but no definite information regarding the proportion of soil nitrogen in the form of amino sugars is yet available. The proportion may not be insignificant since chitin occurs in fungal mycelium, and other polysaccharides containing hexosamine units are synthesized by bacteria. Unfortunately the methods commonly employed for the determination of amino sugars are not suited for soil analysis.

The fact that a considerable fraction—as much as 30 per cent.—of soil nitrogen is resistant to acid or alkali hydrolysis has been taken to indicate that much of this nitrogen is of non-protein nature and has led to the suggestion that part of the organic nitrogen of soils is in the form of heterocyclic nitrogen compounds (65, 66, 70). In this connexion it may be pointed out that Dyck and McKibbin (71) have reported that not all the nitrogen in organic soils is determinable by the Kjeldahl method; in every sample tested the Dumas method gave a considerably higher percentage of nitrogen. This discrepancy in nitrogen values could be attributed to the presence of certain heterocyclic nitrogen compounds or of compounds containing nitrogen linked directly to nitrogen. Workers at Rothamsted, however, have found that the results obtained with soils by the Kjeldahl and Dumas methods are in close agreement.

Recent work by Mattson and Koutler-Andersson (72) suggests that some of the organic nitrogen of soil that is stable to hydrolysis may be in the form of nitrogenous complexes formed in soil by interaction between oxidized lignins and ammonia. They prepared such complexes by autoxidation of lignin in ammonium hydroxide and showed that part of the nitrogen fixed by lignin in this reaction was resistant towards strong acid and alkali. They also showed that lignin was able to fix ammonia in a non-exchangeable form under soil conditions. Studies on the fixation of ammonia by organic compounds of known constitution led them to the view that fixation of ammonia-nitrogen by lignin takes place at the phenolic hydroxyl groups and is preceded by the oxidation of these groups. Bennett (73) obtained evidence in support of this view. Moreover, he found that the nitrogen content of a complex prepared by autoxidation of lignin in ammonium hydroxide was reduced only from 7·22 to 2·66 per cent. by a somewhat drastic methylation procedure. These interesting observations should be provocative of much research, particularly with regard to the form in which ammonia-nitrogen is fixed by lignin.

Evidence for the presence of nucleic acids in soils has been discussed above. Some idea of the proportion of soil organic nitrogen likely to be in the form of nucleic acids can be derived from the ratios of organic nitrogen to organic phosphorus in soils and nucleic acids. Kaila's recent work (34) showed that the average ratio of organic nitrogen to organic phosphorus in 70 Finnish mineral soils was about 8·4. On the basis of this figure and on the assumption that 50 per cent. of the organic phosphorus of soil is in the form of nucleic acids, the ratio of organic nitrogen

to nucleic-acid phosphorus in soil is 16·8 : 1. Since the nitrogen : phosphorus ratio of nucleic-acid preparations is generally about 1·8 : 1, this means that the ratio of nucleic-acid nitrogen to total nitrogen in soil is 1·8 : 16·8. In other words, not much more than 10 per cent. of soil nitrogen is in the form of nucleic acids. This estimate must be regarded as maximal since there is no evidence to suggest that as much as half of soil organic phosphorus is in the form of nucleic acids.

It is obvious from this cursory review that present information regarding the chemical nature of the nitrogenous organic complexes of soil is extremely unsatisfactory and that this problem deserves high priority in any scheme of research on soil organic matter. It is equally obvious that there is no justification for the practice of multiplying the total nitrogen of a soil by 6·25 and returning the result as 'protein'.

The unavailability of soil organic nitrogen

Although proteins, nucleic acids, and other nitrogenous organic compounds are rapidly mineralized when added to soils, not much more than about 1 per cent. of the organic nitrogen of soil is made available during the growing season.

The unavailability of soil organic nitrogen has been the subject of much speculation. Waksman and Iyer advanced the theory that the availability of soil proteins is reduced through combination with lignin, and supported this by studies on the properties of complexes prepared by mixing and then acidifying alkaline solutions of lignin and protein (74–77). Proteins in such complexes were found to be highly resistant to biological decomposition. Waksman and Iyer postulated that lignoprotein complexes are formed in soil by a gradual process which involves condensation of the carbonyl group of lignin with an amino group of a protein.

An entirely different explanation of the unavailability of soil organic nitrogen was provided by the results of Ensminger and Gieseking (78), who found that hydrolysis of proteins by proteolytic enzymes was markedly reduced in the presence of certain clay minerals. The effect of clays on protein hydrolysis was found to depend upon their base-exchange capacity. Where the latter was high, as in the case of bentonite, the effect was very marked; where it was low, as in the case of kaolinite, the effect was insignificant. As shown above, Bower (51) later found that the hydrolysis of nucleic-acid materials by nuclease enzymes was also retarded by clay minerals. Here again bentonite was found to be more effective than kaolinite.

These results suggest that the unavailability of soil organic nitrogen may be partly due to adsorption and stabilization of the nitrogenous organic complexes by clay minerals.

Reference may be made here to recent work by Allison, Pinck, and Sherman (79), who found that inorganic colloids can have an important effect upon the decomposition of organic materials in sand culture. The effect was found to be marked with readily decomposable materials but not with sawdust, peat, and cellulose. It depended largely upon the amount and type of the colloid added. Bentonite had the greatest effect

and kaolin the least. For example, in one experiment with soybeans and corn stover plus urea, the average carbon-retention percentages after 12 months were sand 23, sand plus 10 per cent. kaolin 26, sand plus 30 per cent. kaolin 31, sand plus 10 per cent. bentonite 41. Comparison of the carbon-retention figures in a kaolinitic soil with those in a soil of the montmorillonite type showed no very striking differences, but this may have been due to the higher acidity of the kaolinitic soil or to differences in the percentages of colloids present in the soils. In comparison with quartz sand both soils were effective in holding carbon. Loss of carbon from casein in sand culture was found to be decreased by the addition of colloids.

These results are in harmony with those of Bower and of Ensminger and Gieseking. They suggest that the clay minerals of soil may play an important role in the stabilization of soil organic matter.

The availability of the stable nitrogen isotope, N^{15}, and the carbon isotope, C^{13}, has made it possible to label the nitrogen or carbon in plant materials and to determine how much of the nitrogen mineralized or carbon dioxide evolved when such materials are added to soil is derived from the plant materials and soil organic matter, respectively. Recent work using this technique has shown that the mineralization of soil organic nitrogen and the decomposition of soil organic matter are greatly accelerated by the addition of plant materials (80, 81, 82). For example, Broadbent (81) found that when Sudan grass enriched with C^{13} and N^{15} was incubated with a silt loam for 32 days, about 60 per cent. of the nitrogen mineralized, and about 20 per cent. of the carbon dioxide evolved, came from the soil organic matter. Mineralization of the soil nitrogen was approximately doubled by addition of the Sudan grass and carbon-dioxide evolution from the soil was increased about threefold.

Provided that their interpretation is not affected by isotopic exchange, these results suggest that the unavailability of soil organic nitrogen and the stability of soil organic matter are more apparent than real, and actually due to the absence of energy material to support a vigorous microbial population. Considering its agronomic implications this concept deserves attention. As Broadbent (81) has pointed out, it reconciles the traditional view that soil organic matter is a relatively inert, resistant complex with the well-known practical difficulty of permanently raising the level of soil organic matter.

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CERTAIN PROPERTIES OF THE INORGANIC COLLOIDAL FRACTION OF HAWAIIAN SOILS*

T. TANADA†

WITH the recognition of the important part played by the soil colloidal fraction in determining various physical and chemical properties of a soil, more and more attention has been devoted to finding relationships between these properties and the composition of the soil colloidal fraction. The early investigations were restricted almost entirely to a study of the ultimate chemical composition of the soil colloids; but with the application of X-ray diffraction methods to soil investigation (Hendricks and Fry, 1930; Kelley *et al.*, 1931), an entirely new avenue of approach leading to a knowledge of the proximate composition of soil colloids was opened to the soil investigator. With the use of X-ray technique, chemical analysis, thermal methods, and optical methods, it has become possible not only to identify each mineral species present but also to determine quantitatively its amount in a sample.

Because of the large range in rainfall, the small variations in temperature from one section to another, and the relatively small differences in the chemical composition of parent materials, soils formed in the Hawaiian Islands are ideal to use in a study of the role of rainfall in soil genesis. In this investigation an attempt is made to identify the mineralogical constituents present in soil colloids formed under Hawaiian weathering conditions. Two soils from Tahiti are included in this study.

Until recently most of the investigations dealing with Hawaiian soil colloids have been confined to a study of their chemical composition. McGeorge (1917) has reported on the chemical composition of the clay fraction of several Hawaiian soils. Hough and Byers (1937) have shown that extensive differences exist between the soil colloids developed under weathering conditions in Hawaii and those developed under conditions normally present in continental United States. In a recent publication Hough *et al.* (1941) have devoted considerable attention to the chemical analysis of colloids from fourteen Hawaiian soils.

In one of the first attempts at characterization of the mineral constituents present in Hawaiian soils, Kerr (1928), from equilibrium studies, has expressed the opinion that the alumino-silicate with cation-exchange properties found in a Hawaiian soil is identical with that found in bentonite. Kelley and Page (1942) have claimed that a colloidal sample from Aiea, Oahu, is mainly kaolinitic with some gibbsite or limonite and amorphous material; while those obtained from Naalehu and South Point, Hawaii, contain a large amount of amorphous-appearing material. Their views are based on results obtained from X-ray analyses and

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dehydration studies. A differential thermal analysis of Hawaiian soils has been made recently by Dean (1947).

Description of Soils

With the exceptions of soils Nos. 41–151 and 43–13, all the soils used in this study are surface soils.

Soil No. 37–396 *a*. South Point, Hawaii. Low in organic matter; aeolian. Mean annual rainfall, 15 in.; elevation, sea-level. Geologically very recent.

Soil No. 43–13. Former stream bed, Palama district, Honolulu, Oahu. Clay from 6 in. below surface. Elevation, 50 ft.

Soil No. 37–397 *a*. Naalehu, Hawaii. Mean annual rainfall, 45 in. Geologically very recent.

Soil No. 39–481. Ewa, Oahu. Clay; low in organic matter; residual. Mean annual rainfall, 20 in.; elevation 50 ft. Parent material, basaltic lava; geologically recent.

Soil No. 43–9 *a*. Ewa Plantation Co., Field 52, Oahu. Clay; low in organic matter; alluvial. Mean annual rainfall, 20 in.; elevation, less than 50 ft.

Soil No. 41–148. Honolulu Plantation Co., above mill, Aiea, Oahu. Clay; low in organic matter; residual. Mean annual rainfall, 35 in.; elevation, 500 ft. Parent material, basaltic lava (?); geologically old.

Soil No. 37–491. University of Hawaii, Poamoho Farm, Oahu. Clay; low in organic matter, residual. Mean annual rainfall, 40 in.; elevation, 600 ft. Parent material basaltic lava; geologically old.

Soil No. 40–288. Hawaiian Sugar Planters' Association Experiment Station, Makiki, Honolulu, Oahu. Clay; low in organic matter; alluvial. Mean annual rainfall, 35 in.; elevation 50 ft. Geologically recent.

Soil No. 38–348. Papara, Tahiti. Mean annual rainfall, about 35 in.; elevation, about sea-level.

Soil No. 43–17. University of Hawaii farm, Honolulu, Oahu. Clay; low in organic matter; alluvial. Mean annual rainfall, 35 in.; elevation, 100 ft.

Soil No. 42–38 *a*. University of Hawaii Pensacola Farm, Honolulu, Oahu. Clay; low in organic matter; residual. Mean annual rainfall, 40 in.; elevation, 100 ft. Parent material, volcanic ash; geologically recent.

Soil No. 40–420 *a*. Paauhau Sugar Plantation Co., Hawaii. Clay loam; high in organic matter; residual. Mean annual rainfall, 65 in.; elevation 600 ft. Parent material, volcanic ash; geologically recent.

Soil No. 42–17 *a*. Dowsett Highlands, Oahu. Clay; high in organic matter; residual. Mean annual rainfall, 80 in.; elevation, 400 ft. Geologically old.

Soil No. 41–150 *a*. Kilauea Plantation, Field 6, Kauai. Clay, high in organic matter; residual. Mean annual rainfall, 70 in.; elevation about 400 ft. Parent material, basaltic lava; geologically old.

Soil No. 40–441 *a*. Kilauea Sugar Co., Field 33, Kauai. Clay; high in organic matter; residual. Mean annual rainfall, 100 in.; elevation 400 ft. Parent material, basaltic lava; geologically old.

Soil No. 42–40 *a*. Tantalus, Oahu. Clay; high in organic matter; residual. Mean annual rainfall, 110 in.; elevation, 1,500 ft. Parent material, volcanic ash; geologically recent.

Soil No. 41–147. Hilo Variety Station, Hilo, Hawaii. Clay loam; high in organic matter; residual. Mean annual rainfall, 165 in.; elevation 300 ft. Parent material, volcanic ash; geologically recent.

Soil No. 40–437 *a*. Olaa Sugar Co., Ltd., Hawaii. High in organic matter, residual. Mean annual rainfall, 170 in.; elevation 1,500 ft. Parent material, basaltic lava; geologically very recent.

Soil No. 41–165 *a*. Honomu Sugar Co., Hawaii. High in organic matter; residual. Mean annual rainfall, 230 in.; elevation 1,800 ft. Parent material, volcanic ash, geologically recent.

Soil No. 38–340. Haapape, Tahiti. High in organic matter. Mean annual rainfall, above 100 in.; elevation 900 ft.

Soil No. 41–151. Koolau Range, back of Wahiawa, Oahu. Ceramic clay. Mean annual rainfall, above 200 in. Geologically old.

Analytical Methods

Colloids were separated from the coarser soil materials by the following method. About 50–100 gm. of air-dried soil was placed in a beaker; 100 c.c. of distilled water and 25 c.c. of 30 per cent. H_2O_2 were added. The mixture was heated under low heat on a hot plate. After the H_2O_2 was used up, another 25 c.c. portion was added. This process was repeated until the decomposition of H_2O_2 was not easily discernible. After cooling to room temperature, 200 c.c. of distilled water and 3 c.c. of 10 per cent. NaOH were added, and the mixture was agitated by a high-speed rotary stirrer with glass baffles for 10 minutes. The mixture was then dispersed in 4–5 gallons of distilled water, and after allowing to settle for 24 hours the upper 8 cm. of the suspension was siphoned off. The water siphoned off was replaced, and the mixture again agitated. This process was repeated several times until the desired amount of colloid was obtained.

At first the colloidal suspension thus obtained was flocculated with calcium chloride, but when it was found that colloids from soils high in organic matter were contaminated with insoluble Ca salts, the suspension was flocculated with NaCl after neutralization with dilute HCl. The flocculated material was again treated with H_2O_2. After oxidation with H_2O_2 this colloidal material was centrifuged and washed several times by decantation with a 2 per cent. NaCl solution. Excess NaCl was removed by the same method with 95 per cent. ethyl alcohol. The alcohol was removed with acetone.

Cation-exchange capacity of the samples was determined by the $MnCl_2$ method of Bower and Truog (1940) after the samples were heated at 250° C. for 24 hours. Before the determination, samples were washed twice with *N* NH_4Ac solution of pH 6·8. Free iron oxides were removed by the H_2S method of Truog *et al.* (1936). In one sample free iron oxides were removed by the biological reduction method (Allison and Scarseth, 1942).

The colloidal samples were heated from 100° to 700° C. Temperature interval was 40–50° C. Samples were kept at each temperature until there was no significant loss in weight. From 100° to 250° C. the samples were heated in an electric oven, and above 250° C. they were heated in an electric muffle.

Discussion of Results

The results of the chemical analyses are recorded in Table 1. To facilitate the discussion of results obtained the colloidal samples are divided into five groups. The author wishes to emphasize that this is not a taxonomic grouping and that no claim is made that all colloidal samples extracted from Hawaiian soils fall into one of the five groups or that the lines of demarcation separating each group from the rest are sharply defined. The classification is based mainly on data obtained from chemical analyses and dehydration studies. Factors which play prominent roles in soil formation such as degree of weathering, oxidation conditions, and rainfall are also considered in the classification.

TABLE I

Chemical Analyses of Colloids

	Sample No.	*Cation-ex. cap.*	SiO_2	Al_2O_3	Fe_2O_3	TiO_2	CaO	MgO	K_2O	*Ignition loss*
		per 100 g.	%	%	%	%	%	%	%	%
Group I	37–396 *a*	81·9	54·79	14·02	16·46	2·45	0·63	0·87	0·36	8·60
	(H_2S treated)	46·5	67·75	13·59	7·27	0·75	0·56	1·00	0·33	..
	43–13	81·8	45·28	19·07	19·70	2·38	0·37	1·08	0·38	8·55
	37–397 *a*	89·0	27·02	21·51	20·52	2·72	3·33	0·76	0·16	14·11
	(H_2S treated)	48·3	51·42	17·32	7·17	0·94	5·60	1·94	0·37	..
Group II	39–481	22·8	39·69	32·19	12·67	1·27	0·07	0·41	0·18	13·47
	43–9 *a*	31·9	41·02	28·86	13·37	2·68	0·07	0·43	0·14	12·23
	41–148	16·5	32·56	29·56	17·30	1·95	0·29	0·33	0·43	14·54
	37–491	16·6	33·22	30·05	15·62	1·58	0·40	0·53	1·06	13·50
	(H_2S treated)	14·5	41·49	35·53	3·30	1·54	0·12	0·83	1·65	..
	(Biologically reduced)	20·7	39·92	37·49	2·80	1·75	0·05	0·67	1·49	..
Group III	40–288	54·8	34·52	27·22	18·21	2·65	0·55	0·66	0·61	11·90
	(H_2S treated)	36·8	44·27	28·43	8·90	1·46	0·30	0·94	0·86	..
	38–348	58·9	36·18	28·12	13·15	2·28	1·85	0·64	0·32	14·54
	(H_2S treated)	34·8	45·52	29·31	3·97	0·75	2·66	0·97	0·47	..
	43–17	48·2	34·53	27·30	17·82	2·43	0·21	0·78	0·69	12·88
	42–38 *a*	56·8	36·41	23·59	19·30	2·90	0·13	1·34	0·59	11·64
	40–420 *a*	45·2	27·47	28·56	19·60	3·02	0·05	0·91	0·69	16·10
	42–17 *a*	38·8	26·38	22·76	29·01	2·95	1·71	0·62	0·60	15·77
Group IV	41–150 *a*	33·8	14·35	27·42	31·76	5·74	0·26	0·61	1·16	16·04
	(H_2S treated)	18·8	28·25	31·71	14·03	9·67	0·06	1·23	2·59	..
	40–441 *a*	32·4	6·04	15·56	46·73	10·65	3·53	0·49	0·52	17·67
	42–40 *a*	49·2	14·50	20·58	35·44	4·40	0·09	0·87	0·69	18·52
	41–147	43·2	9·50	15·13	39·89	6·12	3·72	0·34	0·22	19·84
	(H_2S treated)	26·2	36·86	18·12	13·20	3·00	7·69	2·00	1·45	..
	40–437 *a*	57·7	10·09	27·82	28·05	4·21	0·62	0·88	0·05	23·40
	41–165 *a*	37·1	10·74	12·92	52·77	9·95	0·08	0·50	0·78	..
	38–340	55·4	3·64	14·62	47·30	11·01	1·33	0·13	0·15	15·43
	(H_2S treated)	16·0	12·70	20·92	29·70	9·67	0·55	0·76	..	..
Group V	41–151	21·4	48·77	26·98	5·90	4·26	0·18	1·44	4·88	6·97

Group I. The colloids in Group I, which are from very young soils, are believed to be formed in the early stages of the weathering of parent materials. The colloids are characterized by high cation-exchange capacities (about 80 m.e. per 100 g.). Although their iron contents are moderate (15–20 per cent. as Fe_2O_3), there are little indications of much free iron oxides in them. SiO_2 is quite high (30–55 per cent.), while Al_2O_3 is relatively low (15–20 per cent.). MgO tends to be fairly high (about 0·9 per cent.), but K_2O is usually low (less than 0·5 per cent.). Ignition loss tends to be fairly low.

It is believed that with further weathering colloids in this group will more or less acquire the characteristics of the other groups.

Group II. The colloids of Group II are usually formed under conditions of quite low rainfall (less than 40 in. annually). Their

cation-exchange capacities are relatively low (15–30 m.e. per 100 g.). The less weathered colloids of this group tend to have higher cation-exchange capacities than the more weathered ones. Fe_2O_3 is fairly low (10–20 per cent.); SiO_2 is moderate (30–40 per cent.), while Al_2O_3 is usually high (about 30 per cent.). Results from treatment with H_2S or biological reduction indicate that most of the iron in sample No. 37–491 is present as free iron oxide. Results not recorded in Table 1 show that the H_2S treatment affected sample No. 41–148 in a somewhat similar manner as sample No. 37–491. The colour of the colloids of sample No. 43–9 *a*, which was extracted from an alluvial soil, seems to indicate the presence of little free iron oxides. The quantity of MgO in these colloids is usually moderate (about 0·5 per cent.). In the less weathered colloids of this group, K_2O tends to be low (less than 0·2 per cent.), but in the more weathered colloids, K_2O tends to be much higher (0·5–1·0 per cent.). The potassium-containing mineral is probably one of the hydrous micas. Violent decomposition of H_2O_2 when sample Nos. 41–148 and 37–491 were treated with this reagent indicates the presence of free MnO_2. In the colloids of this group ignition loss tends to be moderate.

Group III. Colloids in this group are believed to be formed under moderate rainfall (40–75 in. annually). They are characterized by fairly high cation-exchange capacities (40–60 m.e. per 100 g.). Fe_2O_3 and SiO_2 are moderate (15–30 per cent. and 25–35 per cent., respectively), while Al_2O_3 tends to be fairly high (20–30 per cent.). MgO and K_2O are fairly high (usually greater than 0·5 per cent.). Ignition loss is usually moderate in this group.

It is possible that upon further weathering those colloids subjected to the lower rainfall limits of this group may eventually fall into Group II, while those subjected to the upper rainfall limits may fall into Group IV.

Group IV. Colloids in this group are formed under conditions of high rainfall (greater than 75 in.). They are characterized by moderate cation-exchange capacities (30–50 m.e. per 100 g.). Some of their outstanding characteristics are high Fe_2O_3 content (30–50 per cent.), low SiO_2 content (less than 15 per cent.), and high TiO_2 content (above 10 per cent.). In these colloids Al_2O_3 and K_2O tend to be high at the lower rainfall limits and low at the upper rainfall limits. The quantity of MgO in this group is moderate and tends to decrease with increasing rainfall. Ignition loss is usually high.

Group V. Colloids in this group are believed to be formed under anaerobic conditions and relatively low temperatures and are characterized by the absence of free iron oxides. The colloids in this group were extracted from a ceramic clay. The chemical composition of this sample agrees fairly well with that of the ceramic clay obtained from Koolau Range, Oahu, and described by Wentworth *et al.* (1940). Results which are not included in this paper indicate that the mineral constituents of the colloids in this group are hardly affected, if at all, by the H_2S treatment. The unusually high K_2O content (about 5 per cent.) can probably be attributed to the presence of a large amount of illite or of glauconite. The hydrous micas are known to contain on the average about 5 per cent. K_2O (Alexander *et al.*, 1939).

Effect of H_2S Treatment

The results of the H_2S treatment are shown in Table 2. All samples show some reduction in their cation-exchange capacities after H_2S treatment. Large reductions in cation-exchange capacities are generally associated with large losses in SiO_2, Al_2O_3, Fe_2O_3, or TiO_2. In regard to sample Nos. 37–396*a* and 37–397*a* which are believed to contain little free iron oxides, the association of the loss of large amounts of iron with great reduction in cation-exchange capacities suggests the presence of an iron-containing mineral with considerable cation-exchange capacity. In addition, results obtained from treating sample No. 37–491*a* with the H_2S and the biological methods seem to support this interpretation. Truog *et al.* (1936) have reported that H_2S treatment reduced the cation-exchange capacity of a Hawaiian laterite, and have attributed the results to the presence of an iron silicate. Nagelschmidt (1940) has found that a black earth from Hyderabad, India, containing mainly beidellite, lost much of its cation-exchange capacity after H_2S treatment.

TABLE 2

Effect of H_2S Treatment, Loss or Gain (in g. or m.e.) per 100 g. of Original Sample

Sample No.	*Wt.*	*Cation-ex. cap.*	SiO_2	Al_2O_3	Fe_2O_3	TiO_2	MgO	K_2O
37–396 *a*	−25·8	−47·4	−4·5	− 3·9	−11·1	−1·9	−0·1	−0·1
37–397 *a*	−57·5	−68·5	−5·2	−14·2	−17·5	−2·3	+0·1	..
37–491	−22·8	−5·4	−1·2	−2·6	−13·1	−0·4	+0·1	+0·1
37–491*	−17·7	+0·4	−0·4	+0·8	−13·3	−0·1	..	+0·2
40–288	−31·0	−29·4	−4·0	−7·6	−12·1	−1·7	..	..
38–348	−31·7	−35·1	−5·1	−8·1	−10·4	−1·8	..	..
41–150 *a*	−49·7	−24·3	−0·2	−11·5	−24·7	−0·9	..	+0·1
41–147	−83·3	−38·8	−3·3	−12·1	−37·7	−5·6	..	..
38–340	−75·2	−51·4	−0·5	−9·4	−39·9	−8·6	+0·1	..

* Biologically reduced.

Sample No. 37–491 showed comparatively little loss in cation-exchange capacity following the H_2S treatment. Dehydration studies show that this sample has a large amount of kaolinite in it. From the results it seems that kaolinite is not affected by H_2S treatment. Nagelschmidt (1940) has reported similar results with a red earth from Hyderabad, India, which contain a large amount of kaolinite.

The H_2S removal of the free oxides of samples 41–147 and 38–340 caused a great decrease in the cation-exchange capacity of the colloids of these soils. This treatment caused a loss of 39·8 and 51·4 m.e. of the cation-exchange and a loss of approximately 40 g. per 100 g. of colloid as iron oxide.

According to Table 2, it seems that magnesium and potassium contents of the colloids are not significantly altered by the H_2S treatment. These results suggest that the magnesium- and potassium- containing mineral or minerals present in Hawaiian soil colloids are very resistant to reducing action. This may explain the occurrence of large amounts

of magnesium and potassium in Hawaiian ceramic clays. The H_2S treatment removed large quantities of Fe_2O_3 from colloids which are believed to contain large amounts of free iron oxides (last three samples in Table 2).

Dehydration Studies

Group I. The dehydration curves of the colloids of Group I are typified by that in Fig. 1. The smooth, wave-like pattern traced by the curve is characteristic of this group. A slight loss in weight at 400–500° C. suggests the presence of kaolinite.* From the amount of weight lost in this temperature range, which is the dehydration temperature range of kaolinite, the amount of kaolinite in the colloids is estimated. For an accurate quantitative estimate of kaolinite content it would be desirable to make some correction for losses due to illite and beidellite; but since it is believed that these corrections are small compared to the loss due to kaolinite, no correction is made for the thermal losses due to these minerals. The percentage of kaolinite in this group is estimated to be less than 25 per cent.

Since high cation-exchange capacities are characteristic of this group, it appears that members of the montmorillonite group are present in these colloids. However, deflexions at 500–600° C., which are characteristic of bentonite and beidellite (Kelley *et al.*, 1936), are not observed in any of the dehydration curves. According to Kelley and Page (1942), colloids from Naalehu and South Point show only weak X-ray lines and are believed to contain a large amount of amorphous material. From the dehydration curve of the H_2S-treated sample (37–396 *a*), it seems as if the H_2S treatment did not materially affect the colloids. However, the data in Table 2 show that the H_2S treatment did have a pronounced effect on the chemical composition of this sample.

Group II. Dehydration curves of the colloids in this group are similar to that pictured in Fig. 2. The curves indicate the presence of large amounts of kaolinite in these colloids. This is characteristic of this group. It is estimated that the amount of kaolinite in this group is about 45–60 per cent. or more. This is in conformity with the low cation-exchange capacities of these colloids, since kaolinite is known to have a low cation-exchange capacity. Kelley and Page (1942) have reported that colloids from Aiea are mainly kaolinitic. The dehydration curve of the H_2S-treated sample (37–491) indicates the presence of relatively little hydrated iron oxides and very little, if any, bauxite and diaspore in the colloids of this group.

Group III. A typical dehydration curve of this group is represented in Fig. 3. Colloids formed under the lower rainfall limits of this group have curves that resemble those of Group II, but smaller deflexions in thermal curves indicate the presence of less kaolinite. Those formed under the upper rainfall limits have curves approaching the characteristics of Group IV but with less weight losses below 250° C. The amount of kaolinite in this group is moderate, and ranges from 25 to 40 per cent.

* Use of the word *kaolinite* in this paper refers to the kaolinite group.

Group IV. In Fig. 4 is depicted a typical curve of Group IV. Large losses in weight from 150° to 250° C. are characteristic of this group. These results indicate the presence of large amounts of limonite in the members of this group. Interestingly enough, despite the high Fe_2O_3

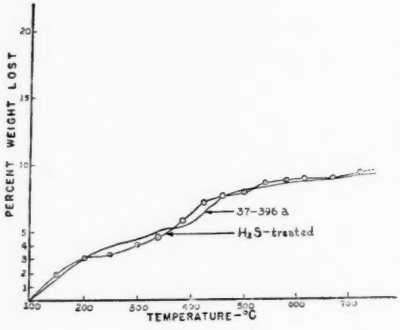

FIG. 1.

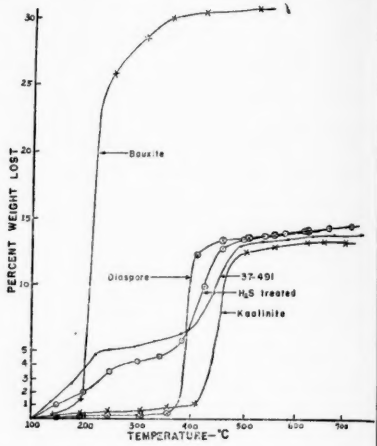

FIG. 2.

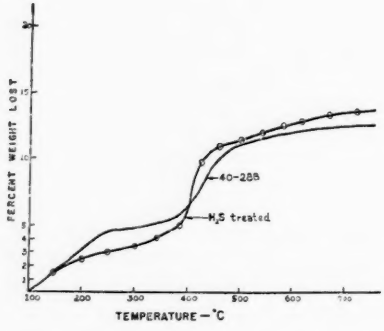

FIG. 3.

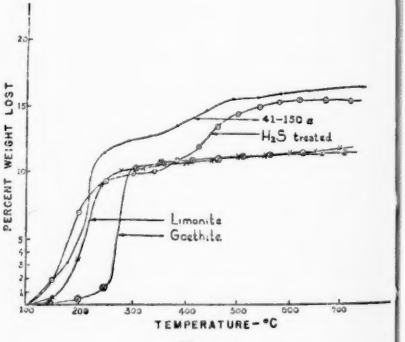

FIG. 4.

FIG. 1. A typical dehydration curve of the colloidal fraction of a soil belonging to Group I.

FIG. 2. A typical dehydration curve of the colloidal fraction of a typical soil representing Group II and also the effect of the removal of the free oxides with H_2S.

FIG. 3. The typical dehydration curve of the colloidal fraction of the soils of Group III.

FIG. 4. The typical dehydration curve of the colloidal fraction of the soils of Group IV.

contents of the colloids, none of the dehydration curves of the colloids shows definite presence of goethite. A very low amount of kaolinite, usually less than 15 per cent., is characteristic of this group. The

dehydration curve of the H_2S-treated sample (41–150) appears to indicate the presence of bauxite in this sample.

Group V. The colloids of Group V are characterized by very little loss in weight below 400° C. (see Fig. 5). A slight deflexion in the dehydration curve at 400–500° C. suggests the presence of a moderate amount of kaolinite. Because of its high K_2O content, this sample is believed to contain a large amount of one of the hydrous micas, probably illite (Wentworth *et al.*, 1940). But, since illite does not have a characteristic

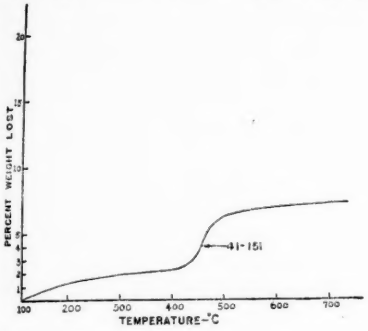

FIG. 5.

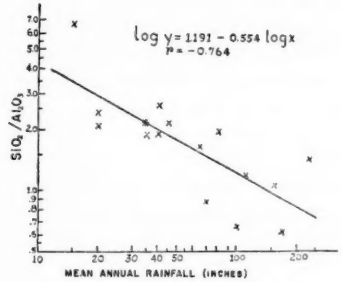

FIG. 6.

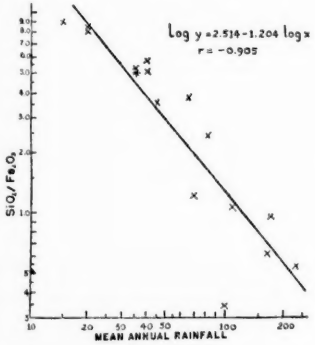

FIG. 7.

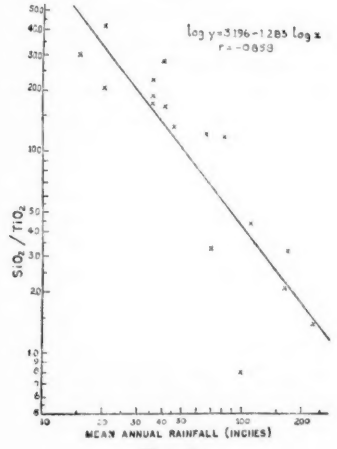

FIG. 8.

FIG. 5. The typical dehydration curve of the colloidal fraction of a soil belonging to Group V.

FIG. 6. The relationship between the SiO_2/Al_2O_3 ratio of the soil colloid and the amount of annual rainfall.

FIG. 7. The relationship between the SiO_2/Fe_2O_3 ratio of the soil colloid and the amount of annual rainfall.

FIG. 8. The relationship between the SiO_2/TiO_2 ratio of the soil colloid and the amount of annual rainfall.

thermal curve (Russell and Haddock, 1940), the use of thermal methods to detect its presence in the colloids is precluded.

General Discussion

It is now the general belief among soil scientists that such factors as climate, biological activity, relief, and age play dominant roles in soil formation (Byers *et al.*, 1938). Many investigators have found relationships between one or more of these factors and certain soil properties. The attempts, however, to relate the kind of clay minerals in soils to weathering conditions and to specific parent rocks have not been very successful (Kelley, 1942).

In this section of this paper attempts are made to relate several chemical constituents in the soil colloids formed in Hawaii with the rainfall and with the degree of weathering. Colloids from soils which are under anaerobic conditions are not considered in this discussion. The colloids from the Tahitian soils are not included in the rainfall relationships.

SiO_2/Al_2O_3 ratio. Using the data obtained by Robinson and Holmes (1924) from representative soils of continental United States, Crowther (1932) has shown that the SiO_2/Al_2O_3 ratio of the clay fraction is related negatively with the annual rainfall and positively with the annual temperature. Jenny (1929), on the other hand, claims that SiO_2/Al_2O_3 ratio decreases with increasing temperature. In Mauritius, where the climate is similar to that of Hawaii, Craig and Halais (1934) have found that the SiO_2/Al_2O_3 ratios of colloids from three mature soils and three immature soils decrease with increasing rainfall. In a study of the chemical composition of Hawaiian soil colloids Hough *et al.* (1941) have found that as freshly formed colloids weather, more silica is lost than alumina.

It can be seen from Fig. 6 that the SiO_2/Al_2O_3 ratios of the colloids decrease with increasing rainfall. The relationship can be represented by the equation,

$$\log y = 1{\cdot}191 - 0{\cdot}554 \log x,$$

where y is the SiO_2/Al_2O_3 ratio of the colloids and x is the mean annual rainfall. The correlation coefficient for this relationship, after adjustment for the small number of samples, is $-0{\cdot}764$ and is statistically significant.

SiO_2/Fe_2O_3 ratio. There is a very strong tendency for the SiO_2/Fe_2O_3 ratio of the soil colloids to decrease rapidly with increasing rainfall. This can be seen in Fig. 7, where the relationship is represented by the equation,

$$\log y = 2{\cdot}514 - 1{\cdot}204 \log x,$$

where y is the SiO_2/Fe_2O_3 ratio of the colloids and x is the mean annual rainfall. The correlation coefficient for this relationship is $-0{\cdot}905$, and is also statistically significant.

SiO_2/TiO_2 ratio. The SiO_2/TiO_2 ratio shows an almost identical trend as the SiO_2/Fe_2O_3 ratio under conditions of increasing rainfall (Fig. 8). Titanium seems to accumulate with increasing rainfall (Hough *et al.*, 1941). This relationship can be expressed by the equation,

$$\log y = 3{\cdot}196 - 1{\cdot}283 \log x,$$

where y is the SiO_2/TiO_2 ratio of the colloids and x is the mean annual rainfall. For this equation the correlation coefficient is $-0{\cdot}858$, and is statistically significant.

Kaolinite content of the colloids. As mentioned previously, the kaolinite content of the soil colloids is estimated by the amount of weight lost by the colloids between 400–500° C. The quantity is estimated to the nearest 5 per cent.

From the data in Fig. 9 it can be seen that the amount of kaolinite in the soil colloids decreases with increasing rainfall. The relationship can be expressed by the equation,

$$\log y = 2{\cdot}901 - 0{\cdot}862 \log x,$$

where y is the percentage of kaolinite in the soil colloids and x is the mean annual rainfall. This relationship has a correlation coefficient of $-0{\cdot}934$ and is statistically significant. One sample from a very immature soil, 37–396 *a*, circled in Fig. 9, was not included in the derivation of the equation.

In connexion with this discussion of kaolinite–rainfall relationship, it should be mentioned that from a study of Australian soils, Hosking (1940) found that under excessive moisture, dominant leaching conditions with free drainage, and no drought conditions, basaltic parent materials give rise to colloids of the kaolinitic type.

Potassium and magnesium content of the colloids. The chemical analyses of the soil colloids show that some of the highly weathered colloids have more total K_2O than less weathered colloids. Perhaps the potassium containing mineral or minerals present in Hawaiian soil colloids are much more resistant than some of the other clay minerals. In order to prove this point it is necessary to find a correlation between the total K_2O content of the colloids and the degree to which the colloids are weathered. Because of the great variations in the geologic ages of the soils from which the colloids are extracted, it appears that rainfall cannot be used as an index of the relative degree of weathering. However, since under conditions of adequate aeration iron should accumulate while silica should decrease as the colloids weather, it is believed that the SiO_2/Fe_2O_3 ratio gives a fair indication of the degree of weathering. For this reason the SiO_2/Fe_2O_3 ratio is arbitrarily taken as a measure of the degree to which the colloids are weathered.

In Fig. 10 are plotted the total K_2O contents of the soil colloids against their SiO_2/Fe_2O_3 ratios. It should be mentioned here that in Fig. 10 the degree of weathering is plotted in a reverse order; that is, the less weathered colloids have a greater SiO_2/Fe_2O_3 ratio than the more weathered colloids. Two samples from very young soils, showing large deviations from the general trend, are not included in Fig. 10. From the trend of the curve in Fig. 10, it can be seen that as the colloids weather the amount of K_2O in the colloids increases up to a certain point (SiO_2/Fe_2O_3 value of 1–2), and then decreases very rapidly with further weathering. Kelley *et al.* (1939) have found that colloids from a highly weathered soil had more potassium than those from a young soil. On

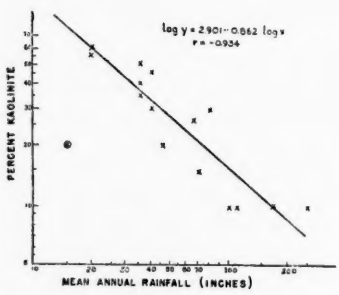

FIG. 9.

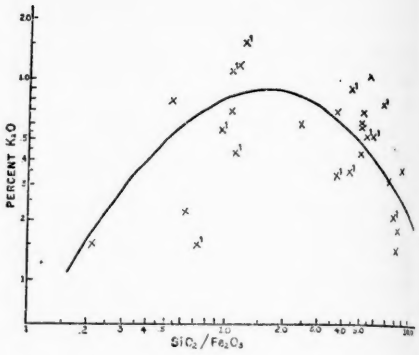

FIG. 10.

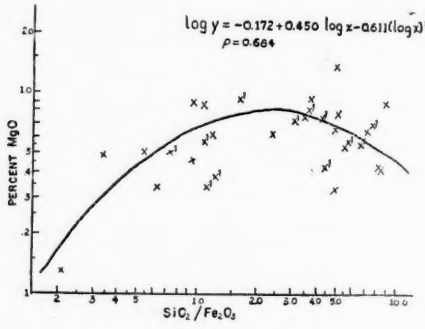

FIG. 11.

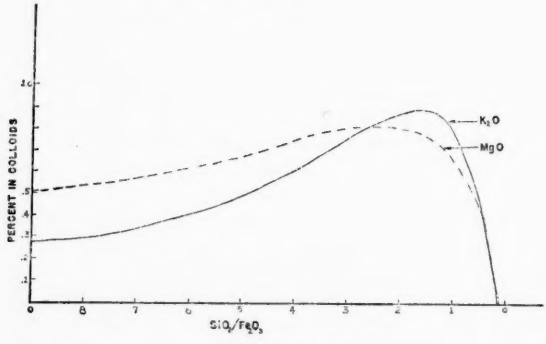

FIG. 12.

FIG. 9. The relationship between the kaolinite content of the soil colloids and the mean annual rainfall.

FIG. 10. The relationship between K_2O content of the soil colloid and degree of weathering. (Data obtained from Hough *et al.* (1941).)

FIG. 11. The relationship between MgO content of the soil colloid and degree of weathering. (Data from Hough *et al.* (1941).)

FIG. 12. The relationship between the K_2O and MgO contents of the soil colloid and their degree of weathering.

the other hand, Bray (1937) has found that the potassium content of the colloids from Illinois soils decreases with development.

The relationship between the total K_2O content of the soil colloids and the degree to which they are weathered can be presented by the equation,

$$\log y = -0{\cdot}094 + 0{\cdot}389 \log x - 0{\cdot}956 (\log x)^2,$$

where y is the K_2O content of the colloids and x is the SiO_2/Fe_2O_3 ratio. The index of correlation for this relationship is 0·640, and is statistically significant. As a further test of this relationship, data from the paper of Hough *et al.* (1941) are plotted in Fig. 10. It can be seen that most of their data follow the general trend of the derived curve. Only two of their K_2O–SiO_2/Fe_2O_3 values, obtained from exceedingly young soils, were badly out of line with the general trend.

The same method of approach is used for the total MgO content of the colloids. The data are plotted in Fig. 11 in reverse order of the degree of weathering. It can be seen (see Fig. 11) that there is a slight, probably insignificant, tendency for the MgO content of the colloids to increase with weathering up to a certain point (SiO_2/Fe_2O_3 ratio of 2–3), and then to decrease rapidly with further weathering. This relationship can be represented by the equation,

$$\log y = -0{\cdot}172 + 0{\cdot}450 \log x - 0{\cdot}611 (\log x)^2,$$

where y is the MgO content of the colloids and x is the SiO_2/Fe_2O_3 ratio. The index of correlation for this relationship is 0·684. This value is also statistically significant. Data from the paper of Hough *et al.* (1941) are also included in Fig. 11. Bray (1937) has shown that the magnesium content of colloids from Illinois soils decreases with development. A comparison of the derived equations for these two elements (see Fig. 12) shows that up to a certain point potassium appears to be weathered out of the soil colloidal complex at a slower rate than magnesium. Beyond this point both are rapidly weathered out at about the same rate.

Summary

It has been found that colloids extracted from several soils from Hawaii and Tahiti have certain properties in common which make it possible to classify them into five groups.

The first group of colloids, formed in the early stages of the weathering of the fresh parent material, has very high cation-exchange capacity; relatively high SiO_2 content; moderate amount of iron which is believed to be present largely as iron silicate; low amount of K_2O smooth, wave-like dehydration curve, and little kaolinite.

The colloids of the second group are formed under conditions of low rainfall. They are characterized by low cation-exchange capacities, moderate amounts of free iron oxides, and high Al_2O_3 and kaolinite contents.

Colloids in the third group are formed under moderate rainfall. Their cation-exchange capacities are fairly high, and their chemical compositions somewhat between that of Groups II and IV. Kaolinite and iron silicates are usually present in moderate quantities.

The fourth group of colloids is formed under high rainfall conditions. Cation-exchange capacity is usually moderately low. This group is characterized by very low SiO_2 content, and high Fe_2O_3 and TiO_2 contents. Limonite is present in large amounts, while kaolinite is in very small amounts. There is no indication of the presence of goethite in these colloids. Bauxite may be present in some members of this group. Results obtained from H_2S treatment seem to indicate the presence of a titaniferous mineral having considerable cation-exchange capacity in some colloids of this group.

The colloids in the fifth group are formed under anaerobic conditions and low temperature. They are characterized by the absence of free iron oxides. Chemical analyses show the presence of considerable amounts of potassium-bearing mineral in them.

It has been found that the SiO_2/Al_2O_3, SiO_2/Fe_2O_3, and SiO_2/TiO_2 ratios and kaolinite content of the colloids decrease with increasing rainfall. The total potassium and magnesium contents of the colloids appear to increase slightly with weathering up to a certain point and then decrease rapidly with further weathering.

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SOME ASPECTS OF THE ALUMINIUM CYCLE

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THE tendency of vegetation to counteract the leaching effects in soils of percolating water has long been recognized for the bases calcium, magnesium, and potassium. Aluminium is usually not considered in this respect because of low uptake by the majority of plants (Joffe, 1936). That there probably is a cycle or circulation of aluminium between soil and vegetation was first appreciated by Polynov (1935, 1944), in his studies of the red soils (krasnozem) of the Black Sea coast in Adzharia, Georgia. The purpose of this paper is to examine and extend Polynov's findings in the light of a comprehensive survey of aluminium in the plant world (Chenery, 1948 *b*, 1949) and to assess the role played by aluminium-plants in soil genesis. Aluminium-plants or aluminium-accumulators are defined as plants with contents of 0·2 per cent. Al_2O_3* or more in their oven-dry leaves. Normal plants, including calcifuges, contain a maximum of less than 0·1 per cent. Al_2O_3, but some accumulators reach 15 per cent. alumina in old leaves about to fall.

Since Polynov's work is to be discussed in detail, it is relevant to cite all his results and conclusions which have some bearing on the aluminium cycle. These are based on a single soil profile.

The Caucasian Forest Soil Profile

This was located in the Caucasian foothills near Batum, where the climate is humid sub-tropical. The parent rocks are labradorite-augite porphyry, but the soil is developed from a clayey red 'crust of weathering' which may be as much as 10 metres thick. The site is the flat top of a hillock under a forest of beech, hornbeam, and chestnut with a shrub layer of rhododendrons. The ultimate analysis of this profile is given below (Table 1).

In connexion with the aluminium cycle the most significant feature of these results is the rise in Al_2O_3 from 22·54 per cent. in the A_1 to 29·84 per cent. in the A_0 horizon, and Polynov (cf. Polynov, 1935) regards this as evidence that podzolization has not taken place. He explains the difference of 7·30 per cent. as being due to absorption of Al_2O_3 by the tree roots in the A_1 and its redeposition in the A_0 horizon via the trees and falling leaves. Despite the fact that his figures show an increase in both Al_2O_3 and Fe_2O_3 down the profile and even an accumulation of the latter in the B horizon, Polynov still maintains that podzolization has not taken place. In fact, in a more recent paper (Polynov, 1948)

* In previous papers the qualifying aluminium content of an accumulator was stated as 1,000 p.p.m. or 0·1 per cent. Al equivalent to 0·189 Al_2O_3. For convenience, this amount has been rounded off to 0·2 per cent. Al_2O_3.

TABLE I

Description	Horizon	Depth cm.	Ultimate analysis % ash: Ash*	Al_2O_3	Fe_2O_3	SiO_2	CaO	pH	$\frac{SiO_2}{Al_2O_3}$
Leaves: Beech (Fagaceae)	..	..	3·09	6·09	1·71	9·40	15·5	..	2·6
Hornbeam (Corylaceae)	..	..	1·96	16·33	0·94	13·30	13·1	..	1·4
Chestnut (Fagaceae)	..	..	2·78	12·67	3·48	2·88	20·9	..	0·4
Rhododendron (Ericaceae)	..	..	3·18	9·21	4·08	3·92	16·9	..	0·7
Mixed Tree Roots	..	..	2·93	32·64	6·94	34·7	6·6	..	1·8
Solum			*Ignited soil*						
Litter	A_{00}	0–3	5·46	15·75	7·49	22·9	23·1	n.d.	2·5
Mor	A_0	3–10	21·43	*29·84*	9·67	46·2	2·12	4·2	2·6
Dark brown clay	A_1	10–15	80·82	*22·54*	14·1	59·1	0·41	5·1	4·6
Lighter brown clay	B	20–25	84·65	26·86	16·6	53·6	0·35	5·0	3·4
Reddish-brown clay	B–C	60–65	88·29	29·31	14·0	53·2	0·52	n.d.	3·1
Crust of weathering; yellowish-brown clay with streaks of tuff-breccia	C	100	88·78	30·01	13·7	53·0	0·12	5·0	3·1
	C	to	90·43	26·82	14·2	56·8	0·06	n.d.	3·6
	C	500	90·93	31·27	12·1	53·4	0·09	5·0	2·9
Parent rock									
Labradorite-augite porphyry	..	..	..	22·4	4·75	55·6	6·70	..	..

The clay minerals are predominately halloysitic with traces of free sesquioxides.
* Ash % material dried at 105° C.

he goes so far as to make the generalized statement that 'the absence of podzolization and the richness of the soils in sesquioxides in the humid sub-tropical red-earth zone are related to the ready absorption of Fe and Al by sub-tropical plants and the almost unbroken growing period which keeps the sesquioxides in continuous circulation'.† This is equivalent to saying that the vegetation has prevented the process of loss of sesquioxides from functioning. Such a sweeping statement prompts the critical examination of the rest of Polynov's figures.

The calcium percentages are instructive as they show clearly how the surface of a base-deficient soil is enriched by continual leaf-fall. That enrichment must take place is self-evident as the average CaO content of the leaves (16·4 per cent.) is 38 times greater than that of the solum excluding the mor (0·43 per cent.) and 184 times greater than that of the crust of weathering (0·09 per cent.). In marked contrast to this, the trend of the Al_2O_3 figures is in the reverse direction. It seems quite impossible that the fall of leaves averaging only about one-third as much alumina as the solum could ever enrich the topsoil.

For all or most of the Al_2O_3 in the A_0 horizon to have come from the A_1, which is described as the zone of root concentration, is also doubtful as a much greater uplift of CaO has taken place and yet the A_1 is not the horizon with minimum CaO content, which is instead the B and red crust of weathering. This suggests that feeding roots did penetrate very much deeper than the A_1 horizon. In view of Polynov's claim that the trees 'energetically' absorb aluminium, an Al_2O_3 profile, at least similar in trend to that of CaO, might be expected as the solum is enriched by Al_2O_3 brought up from lower levels. The solum, however, does not show this but displays the same order of variation in Al_2O_3 content as the crust of weathering. Polynov at the beginning of his paper (1944)

† Abstractor's wording.

stresses that the composition of the red crust of weathering is very variable and that conclusions drawn from one spot would not apply to another and yet he makes a fundamental generalization on the results of only one profile.

TABLE 2

Alumina Content of Oriental Forest Vegetation

Locality	Al_2O_3%*	*Locality*	Al_2O_3%
Beech *Fagus sylvatica* L.			
Akdagh, nr. Amasia, Turkey	0·012	Kastambuli, Turkey	0·031
Oriental Beech *Fagus orientalis* Lipsky			
Polynov's sample	0·187	Djoubia, Black Sea Prov.	0·045
Terek, Caucasus	0·015	Kastambuli, Turkey	0·009
Batum, Georgia	0·010	Djevizlik, Turkey	0·037
Bakuriani, Georgia	0·016	Kure Nahas, Turkey	0·026
Ossetia, Caucasus	0·009	Ardagan	0·021
Kusary, Baku	0·014	Diviaghatch, Azerbaidzhan	0·022
Hornbeam *Carpinus betulus* L.			
Polynov's sample	0·317	Karabagh, Turkey	0·043
Shusha, Georgia	0·020	Kastambuli, Turkey	0·096
Site unknown, Caucasus	0·045	Imamzadeh, Persia	0·028
Site unknown, Caucasus	0·031		
Oriental Hornbeam *Carpinus orientalis* Mill.			
Site unknown, Caucasus	0·020	Amasia, Turkey	0·046
Taurus Mountains	0·034	Trebizond, Turkey	0·031
Chestnut *Castanea sativa* Mill.			
Polynov's sample	0·351	Zonguldah, Turkey	0·028
Site unknown, Caucasus	0·044		
Rhododendron *Rhododendron ponticum* L.			
Polynov's sample	0·293	Site unknown, Kurdistan	0·053
Loristan, Caucasus	0·060	Trapezunt, Post-Dagh	0·027
Tiflis, Caucasus	0·021	N. Anatolia, Turkey	0·084
Site unknown, Caucasus	0·048	Trebizond, Turkey	0·060
Site unknown, Caucasus	0·025	Anatolia, Turkey	0·057
Behizé, Loristan	0·025	Kastanbuli, Turkey	0·049
Mt. Torab, Armenia	0·028	Brummanu, Syria	0·089
Rhododendron *Rhododendron caucasicum* Pall.			
Mt. Kasbek, Caucasus	0·062	Tashala-Staval, Caucasus	0·096
Tzchra-Tzcharo, Georgia	0·064	Site unknown, Kuban Prov.	0·046
British Equivalents of the Oriental Forest			
Beech, Harrow Weald, Middx.	0·020	Hornbeam, Pottern, Wilts.	0·015
Hornbeam, Richmond Park, Surrey	0·076	Chestnut, Bushey Heath, Middx.	0·091
Hornbeam, St. Ippolytes, Herts.	0·020	Chestnut, Cold Waltham, Sussex	0·049

* Al_2O_3 in oven-dried material.

The uplift of alumina by the beech-hornbeam-chestnut forest was regarded with suspicion when it was disclosed that none of these trees

qualified as aluminium-accumulators in the survey of aluminium in the plant world (Chenery, l.c.). Table 3 reveals that the families to which the Caucasian vegetation belong are conspicuously absent. In order to confirm the qualitative tests, leaf samples of the above species (in fruit) were taken from Kew Herbarium specimen sheets and analysed for Al_2O_3. These specimens had all been collected in the 'Orient' botanical region which extends from Syria through Turkey to the Caucasus and Persia. The alumina contents of British examples were also determined for comparison. A modification of the aluminon-thioglycollic acid method (Chenery, 1948 *a*) was employed both for leaves and for soils. In order that a 'Spekker' absorptiometer could be used for this purpose, the volumes of reagent and final solutions were increased 5-fold. The period of heating was also increased to 15 minutes and the subsequent cooling to 6 hours.

It is abundantly clear from Table 2 that Polynov's results are all too high, being from 3 to 20 times as high as those of the 42 other oriental samples. Caucasian vegetation is, in fact, no more aluminous than the same species grown in Britain. Although it is certain that none of the Kew samples came from Polynov's exact locality it is likely that a few would have originated from the red-soil region and even more from other acid soils in which aluminium would have been readily available to the plants.

In view of the foregoing, leaf-fall cannot be regarded as the cause of the comparatively high level of Al_2O_3 content in the A_0 horizon of the Caucasian forest soil. But the idea of a cycle of aluminium between soil and vegetation should not be discarded and will be discussed later in connexion with proved accumulator plants.

Now that the untenability of Polynov's hypothesis has been demonstrated, what alternatives can be submitted to explain his soil results? Four separate possibilities (also hypothetical) may be presented, but combinations of these are conceivable, especially processes 1 and 3.

1. The formation of an immobile and/or insoluble aluminium humate by direct action of the acid mor on the halloysitic clay. Joffe and Watson (1933) explain in a similar manner the greater sesquioxide content of the A_1 horizon of the Lakewood series. They also state that the silicate complexes of the A_1 show a lower degree of disruption compared with the A_2 horizon as a result of the increase in calcium ion content in the A_1 by falling leaves. In order to account for the high humus content of Japanese Ando soils, Mitsui (1948) also postulates the formation of aluminium humates.

2. Abnormal loss of silica by the A_0 horizon through lateral percolation due to permeable overlying much less permeable clay on the top of a hillock.

3. Uplift of aluminium in the soil solution during periods of desiccation, but accompanied here by subsequent fixation as humates, as proposed by Harrassowitz (1930) to explain the occurrence of crusts of sesquioxides in 'lateritic' profiles.

4. Variation in parent material; Polynov's data show that the Al_2O_3

content of the crust of weathering covers the range 26·8–31·3 per cent. A sample from Batum collected by Dr. E. M. Crowther extends this range to 34·9 per cent. Al_2O_3.

Numerous data are recorded showing that Al_2O_3-rich A_0 and A_1 horizons are not uncommon. Such profiles, developed under non-aluminous vegetation, occur in practically every part of the world, and in a great variety of soil groups, but particularly in podzols and podzolic soils. Differences in the Al_2O_3 content of ignited soil of A_0 and A_1 or of A_1 and A_2 horizons range as high as 13·3 per cent. in a Hawaiian Latosol (Sherman *et al.*, 1948), 7·3 per cent. in a Caucasian Krasnozem (Polynov, 1944), and 5·5 per cent. in a Scottish Gley Podzol (Muir, 1934). Aluminium plants are not reported as forming part of the vegetation of any of these soils, and the question arises, what would be the effect of the presence of strong accumulators on the A horizons of a soil?

Soil Genesis under Aluminium-Plants

Before proceeding with this aspect of the aluminium cycle it is desirable to record which plants are accumulators and where they are to be found. A summary of the results over 10,000 tests and quantitative analyses of plant material is presented (Chenery, l.c.).

Aluminium uptake is even more highly specific than Table 3 suggests. All aluminium-plants are calcifuges, but the reverse is far from true—in

TABLE 3

Aluminium in the Plant World

Family	*Tribes or genera*	*Distribution*
	**4 to 15% Al_2O_3 in Oven-dry Leaves*	
Rubiaceae	Cousareae	Tropical S. America
	Psychotrieae	Tropics
Symplocaceae	*Symplocos*	Tropics except Africa
Apocynaceae	*Carpodinus*	Tropical Africa
	2 to 4% Al_2O_3 in Oven-dry Leaves	
Vochysiaceae	Every species	Tropical S. America
Theaceae	Ternstroemieae, Gordonieae	Tropical Asia, SE. U.S.A.
Octoknemataceae	Every species	Tropical Africa
Hydrangeaceae	*Hydrangea* (in part)	China and Japan
Escalloniaceae	*Polyosma*	SE. Asia, Australia
Rhizophoraceae	Anisophylleae	Tropical Africa and Asia
Melastomataceae	Most woody species	Tropics and Sub-tropics
Myrtaceae	*Eugenia* (in part)	S. America
Diapensiaceae	Every species	N. Temperate and Arctic
Proteaceae	Grevilleae (except *Grevillea*)	Australia, S. Africa
Geissolomataceae	*Geissoloma*	S. Africa
Euphorbiaceae	*Aporosa, Baccaurea*	Tropical Asia
	Richeria	Tropical S. America, W. Indies
	Maesobotrya	Tropical Africa
Rapateaceae	Most species	Tropical S. America
Marattiaceae	Every species	Tropics
Angiopteridaceae	Most species	Tropics
Cyatheaceae	About $\frac{2}{3}$ total	Tropics and Sub-tropics
Andreaeaceae	Most species	Cosmopolitan

* These figures represent maxima.

TABLE 3 (*Continued*)

Family	*Tribes or genera*	*Distribution*
	0·5 to 2·0% Al_2O_3 in Oven-dry Leaves	
Winteraceae	*Exospermum*	New Caledonia
Violaceae	*Allexis*	Tropical Africa
	Amphirrhox	Tropical America
Polygalaceae	*Moutabea, Barnhartia*	Tropical America
Xanthophyllaceae	*Xanthophyllum*	Tropical Asia
Diclidantheraceae	*Diclidanthera*	Tropical S. America
Pentaphylacaceae	*Pentaphylax*	Tropical Asia
Scytopetalaceae	*Brazzeia*	Tropical Africa
Icacinaceae	*Leptaulus*	Tropical Africa, Mascarenes
	Gonocaryum	Tropical Asia
Celastraceae	*Kurrimia*	Tropical Asia
Phyllonomaceae	*Phyllonoma*	Central America
Cunoniaceae	*Ceratopetalum, Schizomeria*	Australia
Crypteroniaceae	*Crypteronia*	Tropical Asia
Loganiaceae	*Strychnos* (in part)	Cosmopolitan
Gentianaceae	*Tachia*	Tropical S. America
Lentibulariaceae	*Utricularia*	Tropics and Sub-tropics
Monimiaceae	Mollinedieae	Tropics and Sub-tropics
Lauraceae	*Aiouea*	Tropical S. America
	Litsea, Lindera	Tropical Asia
Juglandaceae	*Carya* (in part)	N. America
Liliaceae	*Aletris* (in part)	Japan, N. America
Matoniaceae	*Matonia*	SE. Asia
Gleicheniaceae	*Gleichenia*	Tropics and Sub-tropics
Loxsomaceae	Every species	N. Zealand, Temp. S. America
Plagiogyriaceae	*Plagiogyria* (in part)	Tropical Asia, S. America
Dipteridaceae	Most species	Tropical Asia
Polypodiaceae	*Blechnum* (3 spp. only)	N. Zealand, N. Caledonia
	Tepeinidium, Cheiropleuria	Tropical Asia
Lycopodiaceae	Most terrestrial species	Cosmopolitan
Polytrichaceae	Most species	Cosmopolitan
Dawsoniaceae	Every species	Australia

fact, often only one or two species of a calcifuge genus growing in the same acid soil as an accumulator show signs of strong aluminium uptake. Further details will be given in a study of the ecology of aluminium-plants. Table 3 indicates their wide geographical distribution and their concentration in the humid tropics. It is noteworthy that no aluminium-accumulating vascular plants were found in the Oriental botanical region, but certain mosses which have this character do occur there.

Despite a thorough search in the literature only two instances were found of vascular aluminium-plants being mentioned in connexion with a particular soil profile, and, even so, the respective authors were unaware of the aluminous association. One of these soils, the Pakihi Gley Podzol of New Zealand, is pictured in Robinson's book (1950) developed under a sward of the aluminous fern *Gleichenia dicarpa* R. Br.; *Lycopodium* spp. are also present, but are not shown in the photograph. The other example is a 'Grood' or Nut-structured Prairie-Forest Soil described by Wilde (1946) as having been developed under a stand of oak and hickory in

southern Wisconsin. The ultimate analysis of this soil shows that podzolization has taken place—'Grood' soils are often described, presumably for this reason, as Grey-brown Podzolic. Data for the A_0 horizon are, unfortunately, not included, for it would have been interesting to have seen whether the aluminous hickory (*Carya* spp.) leaves had manifested themselves. Hickory-oak forests are a major ecological formation in the middle-west of North America and formerly covered vast areas of podzolic soils but not podzols.

The writer has been privileged in having been able to study soils and plants, over a period of 12 years, in a territory abounding with aluminium-plants, namely Trinidad, B.W.I., which is floristically part of the mainland of South America. Beard (1945) in his monograph on the natural vegetation of Trinidad describes several formations which include aluminium-accumulating dominants. Besides dominants and second-story trees, the understory shrubs are more frequently accumulators, both in virgin and second-growth vegetation. The preceding paragraph leads one to anticipate that leaves rich in aluminium cannot obviate the podzolization process of downward translocation of alumina in a soil profile. In order to verify this, sets of soil samples were collected from sites selected at random or, for convenience, inside the aluminous Trinidad forest formations without regard to the exact kind of trees under which the pits were dug. At some time or other in their history the sites would have had aluminium-accumulators overhead and should give more representative results than samples taken directly underneath an accumulating tree or shrub. One Trinidad profile pit (*d*), which had been previously sampled for routine soil-survey purposes, had been deliberately dug in a thicket of aluminium-accumulating second-growth. For comparison shallow profiles under British accumulators were sampled and their alumina contents determined. Aluminium-accumulators are more widespread in Britain than is generally known, but instead of being forest trees they are fern-allies—*Lycopodium* spp.—or mosses—*Polytrichum* spp. and *Andraea* spp. *Polytrichum* spp. are especially common on moorlands and heaths (on soils more or less podzolized), occurring in almost pure swards over areas from a few square feet to many rods. Fern-allies or club-mosses are fairly common above 1,000 ft., as are *Andraea* spp. on rock faces above 1,500 ft. elevations.

Profiles in Trinidad, B.W.I.

a. Red clay under semi-evergreen seasonal forest

One of the dominant trees of the 'Purple heart' fasciation of this forest formation is *Mouriria marshalli* Burtt-Davy et Sandw. (Melastomataceae) which according to Beard comprises 10·9 per cent. of the total number of upper-story trees with a girth over 1 ft. There are 41 other species of trees in this category, but only this species is an aluminium-accumulator. Of the lower-story trees the two accumulators *Rudgea freemani* Sprague et Williams (Rubiaceae) and *Mouriria rhizophorifolia* (DC.) Tri. constitute 2·05 per cent. of the total. Leaves of *M. marshalli*, which are shed in the dry season, probably contain more than 10 per

cent. Al_2O_3 on the oven-dry basis since leaves from a tree in flower contained 8·1 per cent. Al_2O_3 and would persist on the tree for 7 months more. The soil, known as Talparo Clay, is developed on non-calcareous Miocene clay-shale under a rainfall of 50–70 in. per annum; it consists of about 6 in. of dark to paler brown humose clay overlying a few inches of brick-red clay which becomes mottled grey at about 12 in. The parent material appearing at about 30 in. is grey clay stained and mottled with yellowish-brown. Inadvertently, no litter was collected with the soil samples, but the results for the A_1 horizon are, nevertheless, significant in that they show a loss of alumina of 4·5 per cent.

TABLE 4

Horizon . .	A_1	B_2	B_2	B_{21}	C
Depth* . .	6	12	20	32	40
Al_2O_3%†. .	20·4	24·9	24·4	24·2	24·4

b. Yellow loam under lower Montane rain forest

Two species out of 42 in the canopy layer of this forest are aluminium-accumulators—*Richeria grandis* Vahl (Euphorbiaceae) comprising 1·37 per cent. of the total and *Aiouea schomburgkii* Meissn. (Lauraceae) with about 1 per cent. of the total trees. In the lower story *Rudgea freemani* and *Mouriria rhizophorifolia* together with several *Miconia* spp. (Melastomataceae) comprise 7·22 per cent. of the total number of trees in this layer. The shrub layer, when present, often consists of pure stands of the Rubiaceous aluminium-plants: *Cephaelis mucosa* Sw., *Psychotria inundata* Benth., and *Palicourea crocea* (Sw.) R. et S. The sites from which the soil samples were taken were located in the upper zone (*c.* 1,800 ft.) of this forest formation where there is a much greater number of *Richeria* trees than indicated by Beard's survey. Between 1,800 and 3,000 ft. elevation in the same mountain range *Richeria grandis* becomes the dominant tree, comprising 24–7 per cent. of the total canopy according to the situation. Leaves of *Richeria* when they fall will contain at least 5 per cent. Al_2O_3 on the oven-dry basis since a sample from a tree with leaves not at the falling stage and near the test pits contained 4·1 per cent. Al_2O_3.

The soil is developed on micaceous schist of Jurassic age under a rainfall of 100 to 200 in. per annum. It consists of 2–3 in. of dark brown humose loam overlying more or less uniformly coloured, orange-yellow loam, or sandy loam to a depth of at least 8 ft., small schist fragments (1–2 mm.) occur from about 42 in. downwards. Alumina contents of three profiles are shown in Table 5.

Sites 1 and 2 were situated within 50 yards of each other and the more sandy site 3 about ½ mile away.

Apart from the litter of sites 2 and 3 and to a slight extent in the A_1

* All depths are measured in inches continuously from the surface downwards.
† All alumina figures are per cent. Al_2O_3 in ignited soil.

of site 2 the effect of the aluminous vegetation has been negligible. Every profile displays the podzolization effect of progressive downward loss of alumina and in site 1 deposition in the B horizons is apparent.

TABLE 5

Site 1. Richeria grandis ash contained 39·1% Al_2O_3

Horizon	$A_{00}+A_0$	A_1	A_1	B_2	B_2	B–C	C	C	C
Depth	3	6	12	18	30	42	54	66	78
Al_2O_3%	16·6	17·9	17·1	20·6	22·9	19·5	18·3	17·1	17·6

	Site 2					*Site 3*				
Horizon	A_{00}	A_1	A_1	B_2	B_2	A_{00}	A_1	A	A	B
Depth	n.d.	3	6	12	18	n.d.	2	4	12	20
Al_2O_3%	16·1	15·3	14·7	18·7	18·2	13·7	10·6	10·6	10·6	10·9

c. Ground-water podzol under marsh forest (broad-leaved)

Aluminium-accumulators are not among the dominants or upper canopy of this forest, but in the lower story Beard found that the accumulators *Miconia* spp., *Henriettea* spp. (Melastomataceae), *Eugenia baileyi* Britt. (Myrtaceae), and *Mouriria rhizophorifolia* comprised 2·7 per cent. of the number of individual trees present. Aluminium-plants such as *Miconia* spp., *Psychotria* spp., and *Cephaelis* spp. are very plentiful in the shrub layer, while the ground herbs in open sites are almost solely accumulators—*Borreria* spp., *Coccocypselum guianense* (Aubl.) K. Sch. (Rubiaceae), and *Lycopodium cernuum* L.

The soil, known as Valencia Fine Sand, consists of 1 to 4 in. of forest litter; beneath this is 8 to 18 in. of humus-stained, fine quartz sand followed by 3 to 12 in. of whitish quartz sand and gravel (A_2). Below this are the B horizons with 2 to 6 in. of dark brown humus cemented material (B_1) and then a thicker B_2 horizon of hard orange-brown, gravelly iron-pan. Rainfall is 80–120 in. per annum and the whole profile is waterlogged for at least 6 months every year. The land surface then exhibits a series of small, disconnected pools of brown water which fill up the 'hogwallowed' micro-relief.

The alumina content of a typically well-developed profile is as follows.

TABLE 6

Horizon	A_{00}	A_{00}–A_0	A_1	A_1–A_2	A_2	A_2	A_{21}	A_{22}	A_{22}–B_1	B_1	B_{11}	B_2
Depth	n.d.	n.d.	3	6	12	18	24	30	34	45	50	50+
Al_2O_3%	1·25	0·615	0·298	0·344	1·10	1·11	1·58	2·38	3·1	15·0	6·0	11·3

Again, enrichment by Al_2O_3 has taken place in the litter, but is rapidly leached out of the A horizons and deposited in the B.

d. Low humic gley (podzolic) under second growth

The original vegetation of this site was Marsh Forest, but this had been destroyed by felling and/or fire at least 50 years ago. The land appears never to have been cultivated as the characteristic 'hogwallowed'

micro-relief has not been disturbed. The soil, mapped as Long Stretch Silty Clay, is developed on Quaternary terrace alluvium under a rainfall of 50–70 in. per annum. Beneath the litter there is about 3 in. of pale brownish-grey silty or fine sandy clay overlying 18 in. of yellowish-grey silty clay, mottled and speckled orange and yellowish-brown. This changes sharply to greyish-white clay, mottled orange to brick-red. At about 48 in. the ground colour has a definite blue cast and the mottling is purplish-red. As in the Valencia Fine Sand, water stands in the hog-wallows in the wet season, and dry-season desiccation is even more severe. The whole profile is extremely acid in reaction—pH 3·5–4·0. The vegetation on the pit site is a thicket of *Miconia* spp. including *M. acinodendron* (L.) Tri. which has been found in a less acid spot than this, with as much as 12·5 per cent. Al_2O_3 in the oven-dry leaves. The alumina content of the profile is as follows.

TABLE 7

Horizon	A_{0-1}	A_1	B_2	B_2G	$B_{21}G$	CG	CG	CG
Depth	1	3	9	21	34	45	84	96
Al_2O_3%	7·77	8·22	11·9	17·6	22·1	23·1	19·1	19·3

It is evident that the aluminous vegetation has not affected the composition of even the thin A_1 horizon and that podzolization has been unimpeded.

Profiles in Cumberland, England

Immature podzols under Polytrichum *moss swards*

e. From a boggy site in an upland valley near Cleator Moor. Washed samples of the green moss tops (*P. commune* L.) contained 16·6 per cent. Al_2O_3 in their ash while the older brown portions had 25·9 per cent. Al_2O_3—indicating that considerable accumulation had taken place, since the maximum content in the soil was only 21·5 per cent. Al_2O_3. The soil, as sampled, consisted of 3 in. of mor on waterlogged grey clay.

f. From a dry site in an old slate quarry near Ennerdale Lake. A composite moss sample (*P. juniperianum* Willd.) of green and brown tops contained 20·5 per cent. Al_2O_3 in the ash. The soil was very shallow, consisting of about 1 in. of black humose clay overlying orange-brown clay full of slate fragments. The material analysed was first passed through a 2-mm. sieve and then through a 100-mesh sieve to remove slate particles. The alumina contents of these topsoils are:

TABLE 8

	Profile e			*Profile f*		
Horizon	A_{00}	A_0	A_1-B_2	A_0	A_1-B_2	C
Depth	n.d.	3	6	1	4	12
Al_2O_3%	15·5	17·3	21·5	13·1	20·1	25·5

Again no accumulation of alumina has occurred and podzolization has taken its normal course, in spite of the high alumina content of the moss ash.

Discussion

It is apparent from the above data that aluminium-accumulating vegetation has very little effect on the ultimate composition of the soils studied. Since iron-accumulators are extremely rare (Chenery, 1948*b*) it may be concluded that the podzolization process of loss of sesquioxides is practically unaffected by uplift through the vegetation and subsequent leaf-fall. The reason for this lies in the relative smallness of the amounts of aluminium that are circulated and the over-emphasis of these amounts by ultimate analysis figures. Returning to Polynov's results and recalculating them on a total soil and volume basis it will be seen that the mor horizon is definitely less aluminous than the A_1.

TABLE 9

Alumina Content of the Caucasian Forest Soil

	% *Ignited soil*	% *Whole soil*	% *wt./v*	*g.* $Al_2O_3/cm.^2$
A_0 (Mor) . .	29·8	6·38	8·73	0·61
A_1 . . .	22·5	18·2	45·5	2·27

As another example of the way in which ultimate analyses exaggerate the importance of vegetation the following is particularly outstanding: *Andraea petrophila* Ehrh. is a strong aluminium-accumulating moss which grows on wet acid rock faces all over the world; its alumina content on the ash basis is nearly 4 times that of the rock and yet the actual turn-over of alumina is almost negligible as the weight of vegetation is extremely small and the amount of 'soil' produced quite minute. The net effect on the soils of the vicinity is certainly infinitesimal, but the micro-profile data would suggest the reverse.

TABLE 10

Andraea *Moss on Granophyre at* c. *1,900 ft. on Great Gable*

Moss tops . .	52·9	% Al_2O_3 in ash
Middles . .	68·0	
Roots . .	56·3	
Soil . . .	27·4	% Al_2O_3 in ignited material
Rock . . .	16·6	

The data for the polytrichum profiles similarly exaggerate the net circulation of alumina since the ash contents of these mosses are only *c.* 1·0 per cent. and total weights very small. With regard to the aluminous tropical forests where the annual return of vegetable matter to the soil is infinitely greater, the amounts of alumina that are circulated are still relatively small. For leaf-fall to make any impression on a topsoil the time necessary to promote a small increase in alumina content is considerable even if leaching is assumed not to occur. Some idea of this time can be calculated for the Trinidad red clay profile. Assuming that the leaf-fall of the seasonal forest is equal to that of a beech forest in

England which has a maximum of about 350 g. oven-dry leaves per square metre 6 cm. thick, then about 10 per cent. of these leaves would be aluminous and would contain 10 per cent. Al_2O_3 giving a total annual deposit of 3·5 g. per square metre. In order to raise by 1 per cent. (total soil basis) the Al_2O_3 content of the top 10 cm. of a soil with density 2·5, the weight of Al_2O_3 required would be 2,500 g., which would take 700 years to accomplish. For a site under forest to remain undisturbed for this period is not unreasonable, but in this red clay leaching has led to a net loss of 4·5 per cent. in the A_1 horizon. The quantities leached out must, therefore, be considerably greater than the annual return from fallen leaves.

All the soils studied in this paper have been of a podzolic nature. It would be interesting to investigate on similar lines a series of lateritic soils under aluminous vegetation. The writer hopes to follow up this point in central Africa in the near future. There are several other forms of aluminium besides 'total' that could usefully be studied in soil profiles. Of these exchangeable aluminium is of such importance in the ecology of aluminium-plants that it will be the subject of a separate paper.

Summary

The hypothesis of Polynov that the forests growing in the red soils of the Black Sea coast prevent podzolization by uptake of sesquioxides which are subsequently returned to the soil at leaf-fall has been shown to be untenable.

Profiles under proved aluminium-accumulating plants have been examined and no evidence was found that these plants could delay the podzolization process of loss of sesquioxides by leaching.

The need for caution in the interpretation of ultimate analyses has been stressed.

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EFFECTS OF ACID TREATMENT OF SOILS ON PHOSPHATE AVAILABILITY AND SOLUBILITY

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DILUTE acid extractants are widely used to estimate readily soluble phosphate in soils as a guide to phosphate requirements. The extractant commonly used in these laboratories is 2·5 per cent. (by vol.) acetic acid, and it was considered of interest to attempt a direct test of the significance of acetic-soluble phosphate in relation to plant growth. To this end soils from which part of the acetic-soluble phosphate had been extracted were compared with the original soils in pot experiments with oats, and parallel tests carried out with 0·007N. H_2SO_4. The solubility of the phosphate remaining in the treated soils was also tested. Not surprisingly, the effect of removing relatively small amounts of readily soluble phosphate was completely obscured by other effects of the acid treatments.

Experimental

Mitscherlich scale experiment. Twenty-gramme lots of a soil (< 2 mm.) derived from basic igneous rock drift were shaken for 2 hours with 800 ml. 2·5 per cent. (by vol.) acetic acid, the extractions being done in sets of 16. Each set was filtered through a large Büchner funnel and washed free from acetic acid with distilled water. In this way a bulk sample of about 6 kg. of treated soil was obtained and stored moist.

The total P, K, Na, Ca, Mg, Sr, and Mn removed in the filtrate plus washings was determined and the soil restored to its original content of the cations by mixing in the calculated amounts of $CaCO_3$, MgO, K_2CO_3, Na_2CO_3, $SrCl_2$, and $MnCl_2$, the first two in solid form and the remainder in solution. The soil was then moistened, stored moist for 3 days, air-dried, and passed through a 2-mm. sieve.

One-pound lots of the original and the treated soil were mixed with 14-lb. lots of nutrient-free sand for use in Mitscherlich pots. The mixtures were given the full Mitscherlich basal dressing of N, K, Ca, Mg, and Na, but incremental phosphate additions to give four treatments in duplicate in each series, as shown in Table 1. The phosphate was added as superphosphate solution, and the 0·06 g. P_2O_5 addition corresponds to the amount of acetic-soluble P_2O_5 removed from the treated soil. Each pot was sown with 50 oat seeds and later thinned to 35 plants. The differences between the treated and untreated soil were so marked that it was decided to harvest one pot from each treatment at an intermediate stage of growth and to leave only the duplicate to grow to full maturity. In both cases the crop was dried at 80° C., weighed and analysed for P, K, Na, Ca, Mg, and Mn.

Neubauer scale experiment. This covered comparisons of the effects of 2·5 per cent. acetic acid and 0·007N.H_2SO_4 on four contrasting soils, including the basic igneous soil used in the Mitscherlich experiment. The 0·007N.H_2SO_4 was chosen as being very similar in extracting power to the acetic acid. The extractions and the restoration of cations were carried out as already described. The soils are denoted in the tables by the nature of the parent drift; they are all acid (Table 3), with a clay content of about 15 per cent. and a loss on ignition of 8–13 per cent.

One-hundred-gramme lots of soil were mixed with 250-g. lots of nutrient-free sand in Neubauer dishes and given basal dressings corresponding to 1/15th of the normal Mitscherlich dressings, but no P_2O_5. Each dish was sown with 100 oat seeds which were grown for 17 days, harvested according to the standard Neubauer technique, and analysed for P, Ca, and K.

Pot Results

The results for the mature crop from the Mitscherlich experiment are summarized in Table 1. The outstanding feature is that with no P_2O_5 added, the treated soil (from which part of the acetic-soluble phosphate had been removed) gave about 5 times more crop than the untreated soil. The treated soil also gave much higher yields in the two intermediate treatments, but with the full P_2O_5 addition of 1·2 g. the two

TABLE 1

Yield and Composition of Oats from Mitscherlich Pot Experiment with Untreated and Acetic Acid Treated Basic Igneous Soil

P_2O_5 *addition g. per pot*	*Yields—g. D.M. per pot*		*% P_2O_5 in D.M.*		*P_2O_5 uptake—g. per pot*
	Grain	*Straw*	*Grain*	*Straw*	*Grain+straw*
	Untreated soil				
Nil	6·5	6·9	0·61	0·20	0·05
0·06	12·2	11·3	0·49	0·15	0·08
0·12	15·9	15·7	0·58	0·12	0·11
1·20	45·9	53·2	0·69	0·16	0·40
	Acetic acid treated soil with cations restored				
Nil	31·4	34·4	0·29	0·07	0·11
0·06	32·6	40·4	0·37	0·08	0·15
0·12	33·5	47·7	0·33	0·10	0·16
1·20	45·6	55·0	0·78	0·56	0·66

series produced almost identical yields. It appears therefore that the native phosphate in the treated soil was much more available than that in the untreated soil. On the untreated soil, the two intermediate P_2O_5 additions produced clear yield responses, increasing the straw and grain to about the same extent; on the treated soil, they produced clear increases in the yield of straw but had little effect on the amount of grain. This contrast between the two series is probably real and another consequence of the higher phosphate status of the treated soil.

In the first three treatments the percentages P_2O_5 in the crop, especially the grain, are higher on the untreated soil. This is in keeping with the low yields in this series. In the 1·2-g. P_2O_5 treatments, however, where the yields are almost the same, the percentage P_2O_5 is higher on the treated soil, especially in the straw. The total P_2O_5 uptake is higher for the treated soil throughout, reflecting the higher yields in the case of the first three treatments and the higher percentage in the crop in the case of the last one.

The K, Ca, Mg, Na, and Mn in the crop are not included because they show no outstanding differences between the treated and untreated soil. In general, the percentages in the crop either show little variation or tend to fall with increasing yield. The data obtained for the produce harvested at the intermediate stage of growth agree closely with the results for the mature crop.

The results of the Neubauer experiment (Table 2) confirm the above findings. All the acetic acid treated soils show a very marked increase in P_2O_5 uptake by the plants. Except for the granitic soil, the sulphuric acid treated soils also show a marked increase; but apart from the Old Red Sandstone soil, the effect is clearly smaller than in the acetic acid series. The K and Ca values again show no significant effect of the pre-treatments.

TABLE 2

Neubauer Scale Experiment with Acetic Acid and Sulphuric Acid Treated Soils

Pre-treatment of soil	P_2O_5 *uptake by oats—mg.**			
	Basic igneous soil	*Old Red Sandstone soil*	*Slate soil*	*Granitic soil*
Nil	3·1	2·3	3·0	3·2
2 hr. extraction with 0·007N. H_2SO_4 + restoration of cations . .	6·4	5·9	6·0	3·9
2 hr. extraction with 2·5% (vol.) acetic acid + restoration of cations	13·4	5·7	10·5	5·3

* Corrected for initial P_2O_5 content of seeds. Averages of duplicates.

The results of both experiments show that the pre-treatments, including the restoration of cations, increased the availability of the phosphate remaining in the soils, and that this effect completely obscured any effect of removing part of the readily soluble phosphate. The fact that the treated and untreated soil gave almost identical yields when 1·2 g. P_2O_5 per pot was added in the Mitscherlich series is particularly significant (Table 1). So also is the fact that, even with this large amount of phosphate added, the higher uptake from the treated soil still indicates a higher availability. The magnitude of the effect in this experiment is best illustrated by considering the yield from the treated soil with no phosphate added in relation to the response curve for the untreated soil.

When this is done it is found that the increase in phosphate availability in the treated soil, with no correction for the readily soluble phosphate removed, corresponds to the addition of about 0·5 g. P_2O_5 per pot to the untreated soil. This is equivalent to about 150 lb. P_2O_5 per acre. The corresponding comparison on the basis of total P_2O_5 uptake gives, of course, a much smaller, but still very substantial value of 0·12 g. P_2O_5 per pot, equivalent to 36 lb. per acre.

Soil Data

*Bacterial Numbers.** The possibility was considered that one effect of the pre-treatments might be to produce a partial sterilization of the soils. This was checked for the basic igneous soil by following the bacterial number in sand mixtures made from dried untreated soil and dried treated soil with cations restored. The mixtures were made up as in the Mitscherlich experiment, given the full dressing of all nutrients other than phosphate, and stored moist. The bacterial number in all cases increased from about 1 million per g. soil at the start to about 70 million after 14 days and fell to about 50 million after 28 days. There was no appreciable difference between the treated and untreated soil and the initial increase can be attributed to the drying and wetting of the soils. The possibility that the composition of the bacterial population may have been altered in the treated soils cannot be ruled out, but it seems unlikely that there was any differential partial sterilization effect due to the pre-treatments.

Phosphate solubility. The increases in availability were so pronounced that it was reasonable to expect some increase in solubility. The acetic- and sulphuric-soluble phosphate values for the treated soils with cations restored, however, were found to be practically identical with the values for the untreated soils. But the water-soluble phosphate (Table 3, Nos. 1, 2, and 3) is markedly higher in the treated soils. The only exception is the sulphuric treated granitic soil, which also shows comparatively little increase in availability (Table 2). Except for the Old Red Sandstone soil, the solubility is higher in the acetic acid treated than in the sulphuric acid treated soils. Qualitatively, therefore, the solubility increases run closely parallel to the increases in availability. Further, the higher solubilities in the treated soils are not materially attributable to the higher pH of the suspensions. Tests in which the requisite amount of $Ca(OH)_2$ was included in the water suspension of the untreated soil (No. 4, Table 3) show that there was little or no increase in solubility when the pH was raised to that of the treated soil. $Ca(OH)_2$ provides a fair comparison because Ca formed by far the greatest fraction of the cations restored to the treated soils. There is, in any case, no complicating pH difference between the acetic and sulphuric treated soils. It seems clear that the pre-treatments, which included the restoration of cations, increased the inherent solubility of the phosphate remaining in the treated soils.

* Determined by Dr. D. M. Webley.

TABLE 3

P_2O_5 *Solubility (p.p.m. soil) in Untreated Soils and Acid-treated Soils with Cations Restored*

Nature of parent drift	*Basic igneous rock*		*Old Red Sandstone*		*Slate*		*Granite*	
*Extraction**	*pH*	P_2O_5	*pH*	P_2O_5	*pH*	P_2O_5	*pH*	P_2O_5
1. Untreated soil + H_2O	5·8	0·7	5·3	0·5	5·5	1·0	6·0	0·6
2. H_2SO_4-treated soil + H_2O	6·3	1·9	5·8	1·5	6·0	1·5	6·6	0·6
3. Acetic-treated soil + H_2O	6·3	2·6	5·8	1·5	6·0	1·7	6·5	1·0
4. Untreated soil + $Ca(OH)_2$ to same pH as treated soil	6·3	0·8	5·9	0·6	5·9	1·0	6·4	0·4
5. Untreated soil + $Ca(OH)_2$ ≡ pot $CaCO_3$ + salts†	6·4	0·3	6·5	0·4	6·2	0·4	6·8	0·4
6. Untreated soil as in (5) but with $Ca(OH)_2$ as in (4) in addition	6·6	0·3	6·7	0·4	6·4	0·4	7·0	0·4
7. H_2SO_4-treated soil + $Ca(OH)_2$ ≡ pot $CaCO_3$ + Salts	6·5	0·7	6·5	0·5	6·3	0·6	7·3	0·5
8. Acetic-treated soil as in (7)	6·7	0·9	6·6	0·5	6·3	0·6	7·3	0·9

* Soil/Liquid ratio 1 : 10 and 18 hrs. shaking in all cases.

† The $CaCO_3$ added in the Mitscherlich pot experiments was equivalent to 0·67 ml. N. $Ca(OH)_2$ per g. soil. The normalities of the salts in suspensions were approximately

0·002N. NaCl + 0·002N. $MgSO_4$ + 0·01N. K_2SO_4 + 0·01N. NH_4NO_3.

The solubility was also tested under conditions closer to those obtaining in the pots, which received a basal dressing of $CaCO_3$ and nutrient salts. Recent work by Eriksson (1940) and Mattson *et al.* (1949, 1950) has shown that salts markedly reduce the solubility of phosphate in soils and affect the uptake of phosphate by plants. Further, the salt effect on solubility varies with pH, reaching a maximum at about pH 7. The $CaCO_3$ basal dressing was uniform throughout each experiment, and, in view of the pH differences noted above, a materially higher pH might have prevailed in the pots with treated soil. There was therefore some possibility of a differential salt effect on the treated and untreated soils. The Mitscherlich basal dressings were taken as the basis for testing this point. Since the actual concentration of salts in the pot water is uncertain, they were added in 10/1 water suspensions at the same rate per unit weight of soil as in the pots. $Ca(OH)_2$ was added on the same basis. The results (Nos. 5–8, Table 3) show that the pH differences between the treated and untreated soils are smaller than in the water extracts and are hardly significant. Small variations in pH (Nos. 5 and 6) do not, in any case, have any measurable effect on the phosphate solubility under these conditions. The salts reduced the solubility greatly, making it more difficult to detect differences. But except that the difference between the acetic and sulphuric treated slate soil is no longer evident, all the increases previously noted in the water extracts are still clear.

Discussion

The increases in the solubility of the phosphate remaining in the treated soils are probably sufficient to account for the increases in availability. The amounts of P_2O_5 removed in the pre-treatments (3–13 mg. per 100 g. soil), although large compared with the phosphate contents of normal crops, are very small compared with the totals in the soils (266–380 mg. per 100 g. soil). It might be argued that the effects obtained are partly the result of water treatment. But it is unlikely that this can be of much importance. A Neubauer scale test showed that wetting and drying the untreated basic igneous soil, as in the restoration of cations, tended to decrease the uptake of phosphate. Apart from this, the markedly higher effects of acetic acid are proof of a specific acid effect. There can be little doubt that the main increases in solubility and availability are ultimately attributable to the action of the acids as such.

The acid treatments probably produced several changes in the soils, such as removal and deactivation of fixing agents, partial hydrolysis of difficultly soluble phosphates, and conversion of one form of phosphate into another. Very little iron (0·002–0·003 per cent. Fe_2O_3) but an appreciable amount of aluminium (0·1–0·2 per cent. Al_2O_3) was removed. None of this iron and aluminium was restored to the soils, but there is no apparent relationship between the sesquioxides removed and the increases in solubility and availability. On the contrary, sulphuric acid tended to remove more aluminium than did acetic acid but had smaller effects on phosphate solubility. This suggests that the actual removal of iron and aluminium was not an important factor, but it does not rule out the possibility of deactivation of basoid groups—by increased combination with organic matter and other acidoids.

The pH values of the acid suspensions were all between 2·6 and 2·9. This is low enough for extensive attack on several forms of difficultly soluble phosphate, notably apatites and aluminium phosphates, to take place. Partial hydrolysis of such compounds was probably an important factor. The conditions were also favourable for this process to go a stage farther and cause a redistribution of phosphate in the soils. They have high fixation capacities in this pH range, and all the phosphate dissolved by the acids does not necessarily remain in solution but may be partly fixed again. It is well known that such fixation does take place. In general terms, the acid treatments can be expected to bring about a conversion of Ca- and Al-bound phosphate into Fe-bound and adsorbed phosphate. In addition, hydrolysable organic phosphates, such as phytin and carbohydrate phosphates, may be converted into inorganic form in this way. The restoration of cations was an integral part of the pre-treatments, and when the pH is raised such freshly formed phosphate, which is stable at the low pH, must become unstable and more soluble and available than it was in its original form. Such a conversion of Ca-bound phosphate could account partly for the higher pH of the treated soils. The total calcium extracted was restored, but some of it was probably not exchangeable but came from phosphates and other compounds. This may apply also to the other cations. Other possible

factors in this connexion are removal of organic matter and deactivation of acidoid groups.

The results are probably to be largely accounted for along the above lines, and extractions with neutral NH_4F show that the acid treatments increased the adsorbed phosphate content of the basic igneous soil by 14 mg. P_2O_5 per 100 g. soil. But the other soils show no such increase. This contrast is significant because this and similar soils derived from basic igneous rock drift contain appreciable amounts of apatite, whereas the other soils do not.* Conversion of this apatite doubtless accounts for the marked increase in adsorbed phosphate and the relatively large increase in phosphate availability in the basic igneous soil. The mechanism of the increases in solubility and availability, however, probably differed in the different soils. There may also have been other factors involved, such as physico-chemical effects associated with the ionic strength, buffer capacity, and nature of the anion of the extractants. These may account for the higher solubility effects of acetic acid. In this connexion, the possibility was considered that the higher effects of acetic acid on availability might be indirect and due to the formation of certain derivatives which are known to stimulate growth. But its higher solubility effects seem sufficient explanation.

It is noteworthy that the water-soluble phosphate proved very sensitive in differentiating between the treated and untreated soils. The failure of the dilute acids to show any increase in solubility in the treated soils, however, is not surprising because the latter had been stabilized against them. The acid treatments are, of course, much more drastic than any treatment encountered in practice, even where sulphuric acid sprays, sulphur, and heavy dressings of ammonium sulphate are used. Nevertheless, the present results are of interest from the point of view of their implications regarding the changes to be expected in soil phosphate with increasing acidity in the field, the low availability of phosphate in acid soils, and the beneficial effects of liming.

Summary

Pot tests with oats showed that extraction of soils with 2·5 per cent. (by vol.) acetic acid and 0·007N sulphuric acid, respectively, followed by restoration of the cation content and pH, increased greatly the availability of the remaining phosphate. This more than compensated for the readily soluble phosphate removed, and the treated soils gave much higher yields and P_2O_5 uptakes than the untreated soils. On three of the four soils used, treatment with acetic acid resulted in a considerably greater increase than treatment with sulphuric acid. Solubility measurements in water and in a solution of salts, simulating the basal dressings used in the pot tests, also gave higher values for the treated soils.

The solubility increases run parallel to, and are probably sufficient to account for, the increases in availability. The nature of the effect is discussed and it is attributed to a combination of factors, such as:

* Private communication from Dr. R. Hart.

deactivation of fixing agents, partial hydrolysis of difficultly soluble inorganic and organic phosphates, and redistribution of phosphate in the soils. One of the treated soils showed a marked increase in adsorbed phosphate.

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THEORETICAL ERRORS OF HYDROMETER METHODS FOR THE MECHANICAL ANALYSIS OF SOILS

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DURING the last 20 years many soil workers have used hydrometer methods for the mechanical analysis of soils and, practically without exception, have reported results in good agreement with those obtained by standard methods. There has been, however, a tendency to regard all hydrometer methods as essentially empirical in nature and to use them, frequently in conjunction with rapid methods of dispersion, for obtaining approximate results. The theoretical aspects of hydrometer methods appear to have received relatively little attention, with the result that considerable doubt, regarding the factors which control their reliability, still exists.

In his pioneer work, Bouyoucos (1927, 1927 *a*) used a variable immersion hydrometer which was graduated empirically (by means of a soil of known mechanical composition) to read directly in grammes of soil per litre, and he found that the same hydrometer could then be applied to determine the approximate mechanical analysis of many other soils. These results have subsequently been confirmed by other workers, and hydrometers of the Bouyoucos type have been extensively used for obtaining rapid mechanical analyses for agricultural and engineering purposes.

Puri and Puri (1939) have pointed out the importance of keeping the depth of immersion constant and have emphasized the need for *deep* immersion. Their chaino-hydrometer is designed to give constant deep immersion, and the excellent agreement between their hydrometer, and pipette, results affords striking confirmation of the postulates on which the design of their hydrometer is based.

Codoni (1943, 1943 *a*) has given the subject a more theoretical treatment, but much of his work is based on the experimental evidence obtained by examining a large number of soils by hydrometer methods, and consequently his work, though greatly strengthening the position of hydrometer methods, does not completely remove the uncertainty of what would happen when a soil of very abnormal mechanical composition is encountered.

Scope of the Paper

The present paper contains a discussion of the theoretical errors inherent in hydrometer methods when they are used to find the percentage of soil in suspension at a given depth and after a given time of sedimentation. Errors due to experimental technique will not be considered in detail, but will be regarded as absent by assuming that:

(*a*) Dispersion is complete and all organic matter has been destroyed.

(*b*) The hydrometer is inserted sufficiently slowly to avoid mixing the suspension by non-laminar flow.

(*c*) The hydrometer is in equilibrium, i.e. readable, at exactly the correct sedimentation time.

(*d*) The sedimentation has taken place undisturbed by the presence of the hydrometer, i.e. the hydrometer is inserted immediately before the reading is made. (This condition can be only approximately realized in practice by making the time required for (*b*) and (*c*) short in relation to the sedimentation time. Purely experimental errors are accordingly likely to be greater for silt than for clay, and for shallow, than for deep, immersion hydrometers.)

In practically all systems of mechanical analysis, including the international, the ultimate object is to find the summation percentage weight of soil which consists of particles with radii falling between specified upper and lower limits. Two types of error can be made in the experimental estimate of such a percentage:

(*a*) *The first type of error* arises when limiting radii, corresponding to summation percentages found experimentally, are incorrectly estimated. An error of the first type occurs, and is accepted, in all systems of mechanical analysis, which employ Stokes's Law, whenever the soil density differs from the value assumed; but a similar error has formed the basis of much criticism of hydrometer methods, by Keen (1928, 1931) and others, on the ground that the density registered by the hydrometer cannot be related to a definite depth in the sedimenting column.

(*b*) *The second type of error*, which does not occur in pipette or sedimentation methods, arises when the soil density differs from the value assumed in calculating the weight of soil in suspension from the density of the suspension.

Throughout the paper the terms clay, silt, &c., will be understood to refer to the conventional fractions of the international system of mechanical analysis. The conclusions reached are, however, equally applicable to the corresponding fractions in any other system.

Soil Composition Curves and Errors of the First Type

In mechanical-composition curves it is customary to plot summation percentage as ordinate against the logarithm of either settling velocity, radius, or diameter; and, before going farther, the following relationships may be noted. If P = percentage of soil in suspension at depth L and time T, W = the corresponding weight in g./litre, D = density of the suspension at L, and D_1 = density of the liquid in which the soil is dispersed, then

$$P = K'W = K''(D-D_1) \tag{1}$$

or

$$dP = K'dW = K''dD \tag{2}$$

and

$$r^2 = Kv = KL/T \tag{3}$$

or

$$2\log r = \log K + \log v = \log K + \log L - \log T, \tag{4}$$

where K', K'', and K are constants for any particular soil. Thus a curve drawn to express P in terms of $\log r$ or $\log v$ can, by merely changing the origin and scale, be interpreted as expressing the corresponding relationship between density of a suspension and depth at constant time, or time at constant depth.

When a known error of δr is made in determining the radius, the corresponding error in P is of the first type, and is equal to the product of δr and the average gradient of the curve between $\log r$ and $\log(r+\delta r)$ which can only be evaluated if the relationship $dP/dr = \phi(r)$ is known. The function $\phi(r)$ is almost invariably unknown but, when theoretical curves are drawn on the assumption that $\phi(r) = K_1 r^n$ (K_1 = constant), it is found that all the types of curvature and gradient found in the composition curves of natural soils can be reproduced if values of n are selected from the range 0 to -2.

Integration of $dP = K_1 r^n dr$, and conversion of radius to settling velocity, gives:

$$P = C_1 v^{(n+1)/2} + C_2 \qquad (\text{if } n \neq -1) \tag{5}$$

or

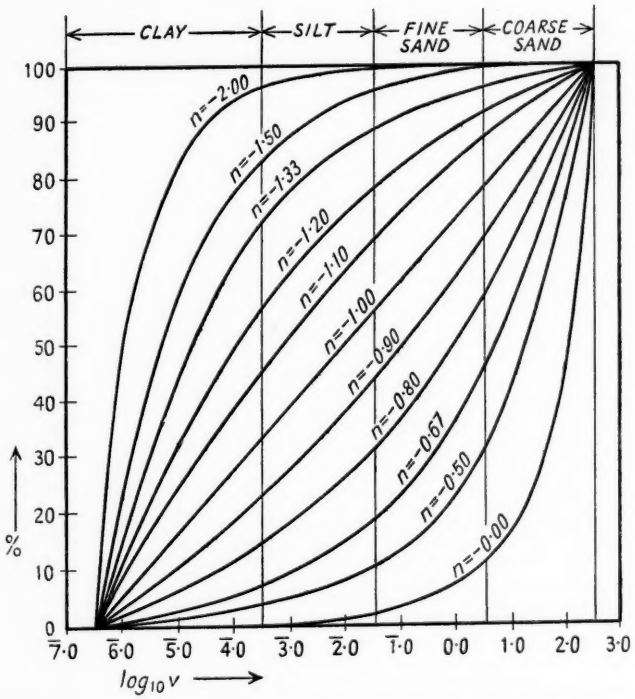
$$P = C_3 \log v + C_4 \qquad (\text{if } n = -1), \tag{6}$$

where C_1 to C_4 are constants, which can be found, for a given value of n, from the boundary conditions. In the case of the fine-earth portion of a soil, the maximum diameter of particles cannot exceed the 2 mm. imposed by sieving, and Robinson (1936) has pointed out that a natural lower diameter limit occurs at about 6×10^{-6} cm. The boundary conditions for the fine-earth fraction of a mineral soil are accordingly $P = 0$ for $\log v = \bar{7}{\cdot}5$, and $P = 100$ for $\log v = 2{\cdot}54$, and, by using these conditions, the theoretical curves shown in Fig. 1 were obtained from equations (5) and (6) by giving n the values shown. A natural extension of this method is to consider the types of curve which would be found in soils where different values of n are appropriate to different classes of particle, and four such curves are shown in Fig. 2.

It will be seen that the majority of the curves in Fig. 1, and all the curves in Fig. 2, are of forms familiar in natural soils, and that all types of curvature and gradient are represented. It is accordingly concluded that, if a suitable value of n is selected from the range 0 to -2, a theoretical curve can be drawn to fit the mechanical-composition curve of any soil between two adjacent points, or, at any rate, to pass through the two points and any selected intermediate point on the soil curve. These interpolation methods, based on equations (5) and (6), will be used later for calculating the sampling depths of hydrometer bulbs in suspensions of soils of different mechanical types, but they do not help in evaluating errors of the first type in an unknown soil.

The order of magnitude of errors of the first type may, however, be estimated by considering the scales found suitable for drawing mechanical-composition curves. For the fine-earth fractions of mineral soils a change of 9 units in $\log v$, $\log L$, or $\log T$ is required to produce a change of 100 in P, and accordingly the *average* gradient of the curve is $dP/(d\log v) = 11{\cdot}1$.* The mechanical composition given by equation (6),

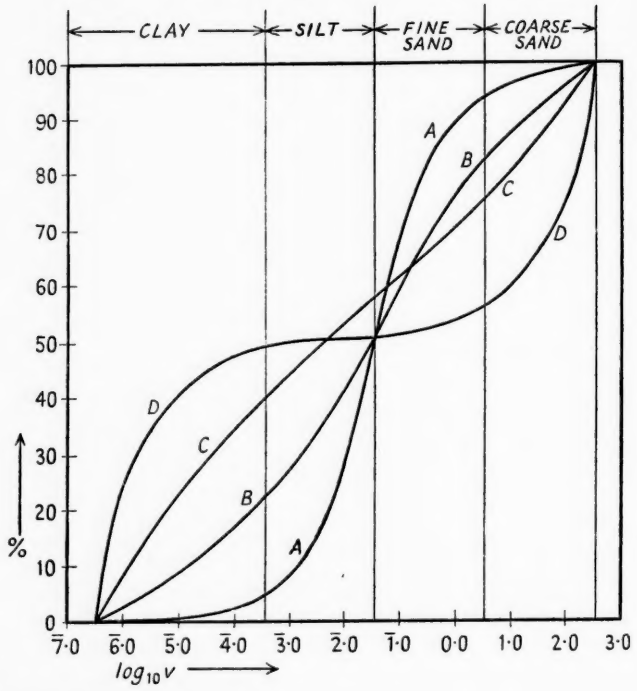
* When organic matter and/or carbonates have been removed by pre-treatment, fractions, gradient, and errors will all be reduced proportionally.



Mechanical Analyses (international) corresponding to the Curves

n	*Clay*	*Silt*	*Fine sand*	*Coarse sand*
−2·00	97·0	2·7	0·3	0·03
−1·50	83·1	11·9	4·0	1·0
−1·33	72·0	16·5	8·0	3·5
−1·20	57·6	21·2	13·0	8·2
−1·10	45·6	22·2	18·4	13·8
−1·00	34·0	22·0	22·0	22·0
−0·90	22·9	20·1	25·4	31·6
−0·80	14·6	16·8	26·8	41·8
−0·67	7·1	11·9	25·7	55·3
−0·50	2·6	6·9	21·7	68·8
0·00	0·1	0·9	9·0	90·0

FIG. 1



Assumptions on which curves are based

Curve A. 50% by weight of soil consisting of particles with radii $>$ 0·02 mm., for which $n = -2{\cdot}0$, and 50% with radii $<$ 0·02 mm., for which $n = 0{\cdot}0$.

Curve B. 50% by weight of soil consisting of particles with radii $>$ 0·02 mm., for which $n = -1{\cdot}3$, and 50% with radii $<$ 0·02 mm., for which $n = -0{\cdot}8$.

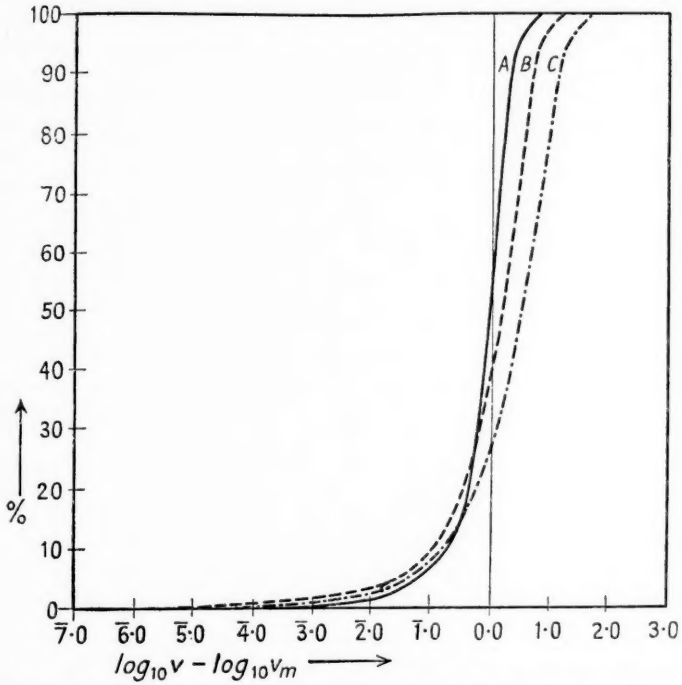
Curve C. 50% by weight of soil consisting of particles for which $n = -1{\cdot}3$, and 50% for which $n = -0{\cdot}8$.

Curve D. 50% by weight of soil consisting of particles for which $n = -2{\cdot}0$, and 50% for which $n = 0{\cdot}0$.

Mechanical Analyses (international) corresponding to the Curves

Curve	*Clay*	*Silt*	*Fine sand*	*Coarse sand*
A	4·8	45·2	44·6	5·4
B	23·1	26·9	33·3	16·7
C	40·9	17·7	18·0	23·4
D	48·5	1·8	4·7	45·0

FIG. 2



Curves based on weights of soil being normally distributed about a maximum at a radius m. v_m = mean settling velocity corresponding to m.

Curve A has $\sigma/m = 0{\cdot}5$
Curve B has $\sigma/m = 1{\cdot}0$
Curve C has $\sigma/m = 2{\cdot}0$

FIG. 3

corresponding to the straight line with gradient 11·1, in Fig. 1, will accordingly be considered to represent the 'average' soil.*

In the 'average' soil, percentage errors of +50 and −33·3, +10 and −9·09, and +5 and −4·76 in estimating v, L, or T will result in errors of ±1·96, ±0·46, and ±0·21 units in P respectively, but in real soils the corresponding errors in P will differ from these average figures according to the local gradient of the curve. For instance, if a soil contains 88·8 per cent. of silt, the local gradient will average 44·4, and the same percentage errors in determining v, L, or T within this fraction will, on the average, produce errors of ±7·84, ±1·84, and ±0·84 in P. On the other hand, if 88·8 per cent. of the soil consists of coarse sand, the corresponding average errors in P, over the remaining fractions, will be reduced to ±0·28, ±0·07, and ±0·03 units.

* This average mechanical composition corresponds to a particle distribution in which $dN/dr = r^{-4}$, where N = number of particles.

In general, very considerable errors in v, L, and T will produce relatively small errors in the mechanical analysis, and there will be a tendency for these errors to be proportional to the size of the fraction being measured. In the international system large errors of the first type would be anticipated in soils with high silt contents, since gradients at both the silt+clay and clay points on the curve would probably be steep. Any such general conclusions can obviously be invalidated by an abnormal distribution of particle sizes, and consequently, for reliable results with all soils, errors in v, L, and T must be made so small that errors of the first kind are negligible even for very steep gradients.

Before concluding this section it may be noted that curves, based on assumptions that maximum percentages occur at a particular radius, are not of types usually found in soils. For instance, if $\phi(r)$ is assumed to be proportional to $[1/\sqrt{(2\pi)}\sigma]e^{-(r-m)^2/2\sigma^2}$, i.e. assuming the weight of soil associated with any radius to be proportional to the probability of that radius occurring in a normal distribution of radii with mean m and S.D. σ, sigmoid curves are obtained when P is plotted against $\log v$. The shape of these curves is determined by σ/m, is entirely independent of the magnitude of m (which, however, fixes the position of the curve on the $\log v$ axis) and, even when $\sigma > m$, the curves are much steeper than those found in normal soils. Three such curves are shown in Fig. 3, and it is interesting to note that they are remarkably similar to the mechanical-composition curves of mechanically disintegrated materials described by Robinson (1936), whose interesting observation, that curves of practically the same form apply to such diverse materials as road metal and air-floated Fullersite, receives a simple explanation from the properties of the theoretical curves. The assumption that numbers of particles are normally distributed about a maximum occurring at some particular radius results in a skew distribution of P and even steeper sigmoid curves than those already considered.

Sampling Depth of the Hydrometer

The densities in a sedimenting soil suspension must obviously increase with depth, and the average density ($\bar{D}$) recorded by the hydrometer bulb will therefore fall between the densities (D_1 and D_2) at the depths (L_1 and L_2) of the top and bottom of the bulb. Accordingly $\bar{D}$ must be the density at some depth $\bar{L}$, between L_1 and L_2, which will be defined as the sampling depth of the bulb. If the density can be expressed as a function of the depth (i.e. $D = f(L)$) over the range L_1 to L_2, and the cross-section area of the bulb at L as the product of its maximum cross-section (A_b) and a function of its distance from the top of the bulb (i.e. $A_b g(L-L_1)$), it can be shown by the methods of elementary hydrostatics that

$$f(\bar{L}) = \frac{\int_{L_1}^{L_2} f(L)g(L-L_1)\,dL}{\int_{L_1}^{L_2} g(L-L_1)\,dL}. \qquad (7)$$

Equations (5) and (6), which were found to represent short ranges of soil-composition curves, can be converted to equations relating density in a soil suspension with depth at constant time by means of equations (1) and (3), giving:

$$D = f(L) = C_5 L^{(n+1)/2} + C_6 \quad (\text{if } n \neq -1) \tag{8}$$

or

$$D = f(L) = C_7 \log L + C_8 \quad (\text{if } n = -1), \tag{9}$$

and it is theoretically possible to find values of the constants C_5 to C_8 and n which will make $D = D_1$, D_2, and $\bar{D}$ when L takes the values L_1, L_2, and $\bar{L}$ respectively. If it is assumed that the hydrometer has a cylindrical bulb, that the volume of the stem can be ignored, and that the horizontal cross-section of the soil suspension is infinite, sampling depths can be found from equation (7) to be:

$$\bar{L} = \frac{2}{n+3}\left[\frac{L_2^{(n+3)/2} - L_1^{(n+3)/2}}{L_2 - L_1}\right]^{2/(n+1)} \tag{10}$$

or

$$\log_e \bar{L} = \frac{L_2 \log_e L_2 - L_1 \log_e L_1}{L_2 - L_1} - 1, \tag{11}$$

and it is interesting to note that the first is, except for the symbols used, identical with the equation given by Codoni (1943 *a*) while the second has been derived by Farmer.* It will be seen from equation (10) that the sampling depth only coincides with the middle of the bulb when $n = +1$, and this corresponds to a very abnormal type of soil.

The effect of a finite cross-section of suspension on the depth at which a hydrometer records density has been studied by Cassagrande (quoted by Codoni, 1943, 1943 *a*), and equations (10) and (11) are applicable to a soil suspension contained in a cylinder of cross-section area A_c if L_2' $(= L_2 - V/A_c$, where $V =$ volume of the bulb) is substituted for L_2 throughout. It will be noted that the depth of immersion of the middle of a symmetrical bulb, $(L_2+L_1)/2$, is equivalent to a depth of $(L_2+L_1)/2 - V/2A_c$ in the suspension before introduction of the hydrometer.

In practice it is necessary to assume that some definite depth in the suspension represents the sampling depth of the hydrometer for all types of soils, and the errors caused by this assumption require to be found. In the following paragraphs the discussion will be confined to hydrometers with symmetrical bulbs and stems of negligible thickness, and an attempt will be made to evaluate the errors caused by assuming that the depth in the suspension, corresponding to the middle of the bulb, is the sampling depth of the hydrometer.

In the case of a suspension of infinite cross-section, it is convenient to express all dimensions in terms of the depths of immersion of the middle of the bulb (L_M) and to use this depth as origin when measuring vertical distances. Let $\lambda\,(= \bar{L}/L_M)$ be the sampling depth, $\alpha\,\{= (L_2 - L_1)/L_M\}$ be the length of the bulb, and x any distance above or below the origin,

* Unpublished work at the Macaulay Institute for Soil Research, Aberdeen.

then, for a symmetrical bulb, it can be shown that:

$$F(\lambda) = \frac{\int_0^{\frac{1}{2}\alpha} \{F(1+x)+F(1-x)\}G(x)\,dx}{2\int_0^{\frac{1}{2}\alpha} G(x)\,dx}, \qquad (12)$$

where capital letters denote functions equivalent to those in equation (7) but adapted to the new origin and scale of measurement. If $F(1+x)$ can be expanded by Taylor's theorem, equation (12) can be written:

$$F(\lambda)-F(1) = \frac{\frac{F''(1)}{2!}\int_0^{\frac{1}{2}\alpha} x^2G(x)\,dx+\frac{F^{iv}(1)}{4!}\int_0^{\frac{1}{2}\alpha} x^4G(x)\,dx+\ldots}{\int_0^{\frac{1}{2}\alpha} G(x)\,dx} \qquad (13)$$

and, provided $G(x)$ can be expanded in a power series of x (a condition fulfilled in all bulbs of normal design), the first term on the right-hand side will be of order $(\alpha/2)^2$ and, if $\alpha < 2$, this will also be the largest term. Accordingly, as α decreases, $F(\lambda)$ will approximate to $F(1)$.

In the case of suspensions of finite cross-section, the procedure is the same, except that it is more convenient to convert all lengths to a scale of $L'_M\,(=L_M-V/2A_c)$, the depth in the original suspension corresponding to the depth of immersion of the middle of the bulb, and it can then be shown that

$$F(\lambda')-F(1) = \frac{\frac{F''(1)}{2!}\int_0^{\frac{1}{2}\alpha'}\left\{x-\theta\int_0^x G(x)\,dx\right\}^2 G(x)\,dx+\frac{F^{iv}(1)}{4!}\int_0^{\frac{1}{2}\alpha'}\left\{x-\theta\int_0^x G(x)\,dx\right\}^4 G(x)\,dx+\ldots}{\int_0^{\frac{1}{2}\alpha'} G(x)\,dx}, \qquad (14)$$

where $\lambda' = \bar{L}/L'_M$, α' = length of the bulb in L'_M units, θ = ratio of maximum cross-section of bulb to cross-section of the cylinder containing the suspension, and the functions denoted by F and G are of the same form as those in equation (13) but adapted to a scale of L'_M. It will be seen that, if A_c becomes infinite, equation (14) reduces to equation (13), for $L'_M = L_M$ (i.e. the scales become the same) and θ becomes zero.

Equation (14) enables the differences $F(\lambda')-F(1)$ to be evaluated for a given set of experimental conditions, and theoretically a solution in the form $\lambda' = \bar{L}/L'_M = 1+e$ can be obtained. The percentage error (E) made in estimating the sampling depth from L'_M is therefore

$$E = 100\times\frac{L'_M-\bar{L}}{\bar{L}} = -100\times\frac{e}{1+e};$$

and equation (3) shows that E is also the percentage error made in determining settling velocity, while the corresponding error in estimating radius is approximately $\frac{1}{2}E$, if E is small.

The magnitude of these errors is determined by the density gradient in the suspension (i.e. by the particle size distribution in the soil) and by the three experimental conditions represented by α', θ, and $G(x)$. Table 1 contains values of E which have been calculated from equation (14) for all combinations of these factors at the values considered, for reasons given below, to cover the range of working conditions.

(*a*) *Particle size distribution.* When the middle of the bulb is taken as origin and lengths are measured on a L'_M scale, equations (8) and (9) may be written:

$$D = F(1 \pm x) = C_9(1 \pm x)^{(n+1)/2} + C_{10} \quad (\text{if } n \neq -1) \tag{15}$$

and

$$D = F(1 \pm x) = C_{11} \log(1 \pm x) + C_{12} \quad (\text{if } n = -1) \tag{16}$$

The following values of n have been considered in preparing Table 1: $+1, 0, -1, -2, -3$. This range is twice as great as was found necessary when considering soil composition curves.

(*b*) *Shape of bulb.* In order to secure maximum volume with minimum length, the bulb should be cylindrical, but, in a practical design, streamlining is obviously necessary, and consequently the symmetrical bulb will be assumed to have its maximum diameter at the middle and to have convex surfaces. All such bulbs (e.g. spheres, ellipsoids, and cylinders with pointed or rounded ends) will have sampling depths between those of a cylinder and a double cone of equal overall length and maximum diameter, and $G(x)$ has been considered for the values 1 and $(1-2x/\alpha')^2$ corresponding to these extreme forms.

(*c*) *Cross-section of suspension.* Two values of θ (0 and $\frac{1}{3}$) have been considered, corresponding to a suspension of infinite cross-section, and to a suspension contained in a cylinder of diameter 1·73 times the maximum diameter of the bulb.

(*d*) *Depth of immersion.* Relative depth of immersion is probably most simply defined as the ratio of length of stem immersed to length of bulb and will be denoted by β. The values $\beta = 1$, 2, and 3·5 have been used in preparing Table 1. The α' required for equation (14) may be found for cylindrical and double conical bulbs respectively by the identities $\alpha' = 2/\{2\beta+(1-\theta)\}$ and $\alpha' = 6/\{6\beta+(3-\theta)\}$.

Table 1 shows that all the percentage errors are positive and that none is very large. The efficiency of increasing the relative immersion in diminishing the error is shown by the average values of E for the three values of β, +0·99 per cent. for $\beta = 1$, +0·35 per cent. for $\beta = 2$, and +0·125 per cent. for $\beta = 3{\cdot}5$, which correspond to increases in $\log_{10} v$ of 0·00427, 0·00149, and 0·00053 units respectively.

The sampling errors of hydrometers with symmetrical bulbs have thus been expressed as small errors of the first type and, as usual, the resulting error in the mechanical analysis cannot be predicted except in general terms. In the case of the 'average' soil already discussed, where $dP/(d\log v) = 11{\cdot}1$, the average errors of the last paragraph correspond

TABLE I

Values of E, the Percentage Error in determining Sampling Depth, for Hydrometers with Cylindrical (C) and Double Conical (D.C.) Bulbs. In all cases E is positive

θ	β	Bulb shape	α'	n				
				-1	0	-1	-2	-3
0	1	C	0·667	0·0	0·9	1·9	2·9	4·0
		D.C.	0·667	0·0	0·3	0·6	0·8	1·1
	2	C	0·400	0·0	0·4	0·7	1·1	1·3
		D.C.	0·400	0·0	0·1	0·2	0·3	0·4
	3·5	C	0·250	0·0	0·1	0·3	0·4	0·5
		D.C.	0·250	0·0	0·0	0·1	0·1	0·2
$\frac{1}{3}$	1	C	0·750	0·0	0·5	1·0	1·6	2·1
		D.C.	0·692	0·0	0·2	0·4	0·6	0·8
	2	C	0·429	0·0	0·2	0·3	0·5	0·7
		D.C.	0·409	0·0	0·1	0·1	0·2	0·3
	3·5	C	0·261	0·0	0·1	0·1	0·2	0·2
		D.C.	0·254	0·0	0·0	0·0	0·1	0·1

to errors in estimating P of $+0{\cdot}047$, $+0{\cdot}017$, and $+0{\cdot}006$ respectively, and consequently the local gradient of the composition curve would have to be exceedingly steep to cause serious errors in a mechanical analysis. In any case, a suitable choice of β makes the errors less than those associated with measuring length and time in pipette sampling; thus the average error of 0·125 per cent., when $\beta = 3{\cdot}5$, is equivalent to 1 second in $13\frac{1}{2}$ minutes, or 0·35 mm. in 28 cm., when sampling for silt+clay, and to 1·3 minutes in $17\frac{1}{2}$ hours, or 0·28 mm. in 22 cm., when sampling for clay.

Throughout the foregoing discussion the volume of the stem of the hydrometer has been ignored. It has thus been tacitly assumed that the density measured by the hydrometer ($\bar{D}_h$) is the average density recorded by the bulb ($\bar{D}_b$), and the error caused by this assumption can be shown to be:

$$\bar{D}_h - \bar{D}_b = -(\bar{D}_b - \bar{D}_s) \times \frac{v}{V+v}, \tag{17}$$

where $\bar{D}_s$ = average density recorded by the stem, and V and v are the volumes of the bulb and stem respectively. It will be noted that, since $\bar{D}_b > \bar{D}_s$ in a sedimenting column, $\bar{D}_h$ is always an under-estimate of $\bar{D}_b$.

The percentage error in the corresponding summation percentages can be found, by equation (1), to be:

$$\frac{P_h - P_b}{P_b} \times 100 = -100 \times \left(1 - \frac{P_s}{P_b}\right) \times \frac{v}{V+v}, \tag{18}$$

and, if the suspension is uniform, $P_s = P_b$ and no stem error occurs, while, if no soil is in suspension above the top of the bulb, this error becomes a maximum. In a soil suspension, $P_s = 0$ at the surface and increases, rapidly at first and then more slowly, to nearly P_s at the base

of the stem, and accordingly it may be assumed, in calculating a maximum value for the stem error, that the density is a linear function of depth, i.e. that $P_s = \frac{1}{2}P_b$. As an example, if $V = 100$ ml. and $v = 0{\cdot}7$ ml. (corresponding to a stout wire, 2 mm. in diameter, immersed to a depth of 22·3 cm.), the percentage error made in determining P_b from P_h would be only about $-0{\cdot}35$ per cent., i.e. a silt+clay, or clay, fraction of 50·00 per cent. would be estimated as 49·83 per cent.

It will be noted that the error due to taking the middle of the bulb as equivalent to the sampling depth is of opposite sign to the 'stem error' and, consequently, when large it will tend to neutralize the latter. This compensation effect may help to explain the good results so frequently obtained when shallow immersion hydrometers with thick stems are used.

Effects of Soil Density

Hitherto errors in determining suspension density and settling velocity have been considered and, where it has been necessary to convert to summation percentage or particle radius, it has been assumed that K'' in equation (1), and K in equation (3), are constants with known values. This assumption is not strictly justifiable since both K and K'' are functions of the soil density.

Effect of density on Stokes's Law. The errors arising from this cause are shared by all systems of mechanical analysis in which fractions are defined in terms of particle radius but determined experimentally from a settling velocity derived from the radius by assuming that all soil particles have a certain density.

For the present purpose, Stokes's Law may be written

$$v = (D_s - D_1)Ar^2, \tag{19}$$

where A is a function of temperature, &c., which will be regarded as a constant, D_s = soil density, and D_1 = density of the liquid in which the soil is suspended and which will be taken as unity. Let P be the summation percentage associated with a maximum radius r and let D_s be the density of the soil particles, then the corresponding settling velocity is $v = (D_s - 1)Ar^2$. But, if (as in the international method) a soil density of 2·6 is assumed, the settling velocity used experimentally will be calculated from $v_c = 1{\cdot}6Ar^2$, and accordingly the error made in the analysis is of the first type and equivalent to a percentage error in determining v given by

$$\frac{v_c - v}{v} \times 100 = 100 \times \frac{2{\cdot}6 - D_s}{D_s - 1}. \tag{20}$$

Once again, the errors in P can only be related to these errors in v by considering hypothetical slopes in the soil composition curve, but it will be seen that P is over-estimated if $D_s < 2{\cdot}6$, correctly estimated if $D_s = 2{\cdot}6$, and under-estimated if $D_s > 2{\cdot}6$. The percentage errors in v, at different soil densities, are shown in Table 2, which also includes equivalent errors in log v, and the errors in estimating P for a soil with the 'average' mechanical composition where $dP/(d \log v) = 11{\cdot}1$. It will

TABLE 2

Theoretical Errors of the Pipette and Hydrometer Methods when the Soil Density is as shown in the first column but has been assumed to be 2·6

	Stokes's Law effect Pipette and hydrometer			*Suspension density effect Hydrometer*	*Mechanical analysis of 'average' soil*					
					Pipette (A only)			*Hydrometer (A and B)*		
D_s	% *error in v*	*Error in log v*	*Error in P (A)*	% *error in P (B)*	% *clay +silt*	% *clay*	% *silt*	% *clay +silt*	% *clay*	% *silt*
2·0	+60·0	+0·204	+2·26	−18·7	57·9	35·7	22·2	47·1	29·0	18·1
2·1	+45·5	+0·163	+1·81	−14·9	57·4	35·2	22·2	48·9	30·0	18·9
2·2	+33·3	+0·125	+1·39	−11·4	57·0	34·8	22·2	50·5	30·8	19·7
2·3	+23·1	+0·090	+1·00	−8·2	56·6	34·4	22·2	52·0	31·6	20·4
2·4	+14·1	+0·058	+0·64	−5·2	56·2	34·0	22·2	53·2	32·2	21·0
2·5	+6·6	+0·028	+0·31	−2·5	55·9	33·7	22·2	54·5	32·9	21·6
2·6	0·0	0·000	0·00	0·0	55·6	33·4	22·2	55·6	33·4	22·2
2·7	−5·9	−0·026	−0·29	+2·3	55·3	33·1	22·2	56·6	33·9	22·7
2·8	−11·1	−0·051	−0·57	+4·5	55·0	32·8	22·2	57·5	34·3	23·2
2·9	−15·8	−0·075	−0·83	+6·5	54·8	32·6	22·2	58·4	34·7	23·6
3·0	−20·0	−0·097	−1·08	+8·3	54·5	32·3	22·2	59·0	35·0	24·0
3·1	−23·8	−0·118	−1·31	+10·1	54·3	32·1	22·2	59·8	35·3	24·5
3·2	−27·3	−0·138	−1·53	+11·7	54·1	31·9	22·2	60·4	35·6	24·8

be seen that, with the 'average' soil, errors are only appreciable when D_s is very different from the assumed value, but, even for a difference of $\pm 0{\cdot}1$, the errors are about 50 times larger than the average error in sampling depth of a hydrometer bulb with $\beta = 3{\cdot}5$. These errors do not affect the sum of all the fractions since any loss of material in one fraction will be gained by another.

Effect of soil density on suspension density. The hydrometer measures density in a suspension which requires to be converted to a summation percentage. With the previous symbols, the weight of soil in suspension, as g./litre, is given by:

$$W = \frac{1000 D_s}{D_s - D_1}(D - D_1), \tag{21}$$

and this can be converted to the summation percentage by the approximate* relationship:

$$P = \frac{W}{M} \times 100 = \frac{10^5}{M} \times \frac{D_s}{D_s - D_1} \times (D - D_1). \tag{22}$$

Suppose a certain value of suspension density (D) has been found in a suspension where $D_1 = 1$. The true summation percentage (D), corresponding to this density, can be calculated from equation (22) only if D_s

* It can be shown that $P = \frac{W}{M} \times 100 \times \frac{1000 D_s - M}{1000 D_s - W}$, but, unless M is of the order 50 to 100 g. (as it is in some of the Bouyoucos methods), the approximate equation (22) is satisfactory.

is known; but, if D_s is unknown and *assumed* to be 2·6, the calculated summation percentage (P_c) will be erroneous whenever D_s differs from 2·6. In this case the error is of the second type which can be expressed as a percentage error in P:

$$\frac{P_c - P}{P} \times 100 = \frac{D_s - 2{\cdot}6}{1{\cdot}6D_s} \times 100. \qquad (23)$$

Accordingly P will be over-estimated if $D_s > 2{\cdot}6$ and conversely, which is the opposite of the effect of soil density previously considered, but it will be seen from Table 2 that these errors are much greater, at least for a soil approximating to the 'average' mechanical composition.

The percentage errors in the clay and silt fractions are not the same unless their densities are equal, and, as silt densities are more likely to be variable than those of clay, the greatest errors are to be expected in the silt fraction. One interesting consequence of this type of error is that the sum of all fractions in a mechanical analysis (where clay and silt are found by a hydrometer, and sand by weighing) will only be 100 per cent. if the correct soil density has been assumed.

Combined effects of errors due to soil density. It has been seen that incorrect assumptions regarding the density of the soil lead to an error of the first type in all the usual systems of mechanical analysis, while, in hydrometer methods, an error of the second type, and in the opposite direction, is super-imposed. The resultant error depends on the local gradient of the soil composition curve and on the size of the fraction, and consequently varies from soil to soil. Table 2 contains the clay and silt contents of the 'average' soil (gradient 11·1, clay 33·4 per cent. and silt 22·2 per cent.) which would be obtained by pipette and hydrometer methods if the soil density had the values shown but was assumed to be 2·6 when doing the analysis. It will be seen that the hydrometer errors are much greater than those due to Stokes's Law.

Summary and Conclusions

A series of theoretical curves, based on the differential equations $dP/dr = Kr^n$ with values of n from 0 to -2, have been shown to represent the various types of curvature found in the mechanical-composition curves of natural soils. These equations have been used to evaluate the errors made when the sampling depth of a symmetrical hydrometer bulb is taken to correspond to the immersion depth of its middle, and the error due to the stem has also been considered. It has been shown that the errors from both these sources can always be reduced to negligible dimensions provided the hydrometer is of constant immersion (i.e. Nicholson's) type and includes the following features in its design:

(*a*) A symmetrical bulb which should be as nearly cylindrical as possible, consistent with adequate streamlining.

(*b*) A depth of immersion such that the length of stem immersed is 3–4 times the overall length of the bulb.

(*c*) A stem which is very thin in relation to the size of the bulb. (This feature, introduced to minimize stem error, also ensures sensitivity.)

Two errors, due to incorrect assumptions regarding the density of soil particles, have been considered, of which one occurs in all systems of mechanical analysis and consequently does not affect the relative merits of pipette and hydrometer methods. The other, which does not affect pipette methods, takes the form of a percentage error in the estimates of the clay and silt fractions given by the hydrometer, but, when large errors of the kind occur, their presence will be shown by the sum of all fractions of the mechanical analysis differing considerably from 100 per cent.

It is accordingly concluded that the only important error made by using a suitably designed hydrometer, instead of a pipette, for a mechanical analysis, occurs as the result of an abnormal density in the material in suspension. Considerable errors can result from this cause; consequently the destruction of soil organic matter, before an accurate hydrometer method is used, is obviously desirable. In the absence of organic matter, determinations of silt are likely to be less accurate than those of clay, both on account of greater variability of particle density and greater experimental error.

Notes on Hydrometers of the Bouyoucos Type

The theoretically desirable features in design are all present in Puri's chaino-hydrometer but are notably absent in hydrometers of the Bouyoucos type, and consequently the good experimental results so frequently obtained with the latter are, at first sight, surprising, but can be explained by the average properties of soil composition curves. It has been seen that quite considerable errors in sampling depth, and sedimentation time, are very unlikely to produce serious errors in the mechanical analysis and, in addition, the effect of the very large errors in the sampling depth, due to variable immersion, will be minimized since a steep gradient at one part of the composition curve reduces the average gradient of the remainder. Thus, if time of sedimentation is approximately correct for the depth of immersion when the hydrometer is registering 50 g./litre of suspended matter, the effect of the large sampling depth error when 5–10 g./litre is being recorded, after the same sedimentation time, will be greatly reduced by the small average gradient in the clay and silt fractions of a very sandy soil.

The satisfactory approximate results are thus seen to depend on the properties of average soils, and serious errors can theoretically occur if the mechanical composition of the soil is very abnormal. Keen's (1928) criticism of the Bouyoucos hydrometer on account of its ill-defined sampling depth, and his conclusion that the method is 'essentially qualitative', are obviously justified; but, in the writer's opinion, sampling depth errors cannot be considered to be a limiting factor in the accuracy of a correctly designed hydrometer of the constant immersion type.

Bouyoucos hydrometers are generally used in conjunction with rapid methods of dispersion in which organic matter is not destroyed. Consequently, even if complete dispersion can be effected, errors due to the low density of organic matter will be considerable, and the destruction

of organic matter in the 50–100 g. of soil, required for the rather insensitive standard Bouyoucos hydrometer, would be difficult to carry out.

There is thus very little doubt that rapid methods of mechanical analysis, based on the Bouyoucos hydrometer, are very useful when applied to essentially mineral soils of types which are dispersed satisfactorily by the method employed. Since soils of very abnormal mechanical composition are rare, it is probable that serious errors in the results obtained are more often due to incomplete dispersion than to the hydrometer itself.

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